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Review Article

Current Trends in Effectiveness of Robotic Assisted Gait Training (RAGT) for Gait Recovery in Neuro Rehabilitation - An Evidence-Based Scoping Review

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ABSTRACT

Robotic-assisted gait training plays a pivotal role in the rehabilitation of individuals recovering from post-stroke and post-spinal cord injuries. By employing sophisticated robotics, this therapy facilitates repetitive, task-specific movements essential for relearning walking patterns. The precision and customisation of robotic systems ensure tailored interventions targeting specific impairments. Moreover, these technologies provide real-time feedback, enhancing patient engagement and motivation. In this review, 11 articles were finalized for review, five were for post-stroke rehabilitation and 6 for spinal cord injuries.

Results show that there is improvement in Spatiotemporal parameters of gait, functional outcomes and quality of life.

In Conclusion, robotic-assisted gait training ultimately accelerates recovery, improves functional outcomes, and restores independence, profoundly impacting rehabilitation effectiveness.

KEYWORDS: Assistive technology, Robotics, Gait parameters, Neurorehabilitation, Functional outcome

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INTRODUCTION

Improving gait recovery is one of the main goals of neurorehabilitation, especially in situations like post-stroke and spinal cord injuries, where many patients find it challenging to walk independently in the community after being discharged from the hospital. Intense, repetitive, goal-oriented techniques that actively involve the person are essential for improving gait because they speed up functional recovery and the restoration of a healthy gait after a stroke [1].

Stroke, characterised by a disruption in brain function due to compromised blood supply, often results in unilateral limb paralysis, corresponding to the affected brain area's dysfunction [1]. It stands as a leading cause of severe adult disability worldwide, with its prevalence escalating alongside global population growth and ageing [2].

Individuals afflicted by stroke commonly exhibit mobility, balance, and coordination deficits, significantly impeding their activities of daily living (ADL). The global burden of stroke is increasing dramatically [3], with 16.9 million people suffering a stroke each year and a global incidence of 258/100,000/year [4]. Each year worldwide. In India, the cumulative incidence of stroke ranged from 105 to 152/100,000 persons per year, and the crude prevalence of stroke ranged from 44.29 to 559/100,000 persons in different parts of the country during the past decade [5].

Typical gait deficits in lower-limb-affected post-stroke individuals involve a combination of impaired muscle strength, coordination, proprioception, and often excessive muscle tone in the paretic limb [6]. The two most immediate biomechanical effects of these impairments are instability of the paretic leg during the stance phase of gait (i.e., the potential of knee instability in flexion or hyperextension) and insufficient foot clearance on the paretic side during the swing phase of gait. To mitigate these deficits, post-stroke individuals typically employ compensatory actions [7].

Spinal cord injury (SCI) is indeed a significant medical challenge globally, affecting thousands of individuals each year. It is a traumatic event with an incidence of 3.6–195.4 cases per million worldwide, 17,810 cases per year in 2020 in the United States, approximately 5000 cases per year, and approximately 200,000 in total in 2010 in Japan [8]. In India, the most common age group at which spinal cord injury occurred in both males (55%) and females (44%) was 20 to 40 years of age. Despite advancements in medical treatment and rehabilitation, functional recovery remains incomplete for many patients, leading to long-term motor disabilities and various secondary complications associated with prolonged wheelchair use [9,10]. Even after rehabilitation, Patients cannot perform independent standing and walking [11].

The emergence of wearable robotic exoskeletons (WREs) presents a promising avenue for enhancing the quality of life for individuals with SCI [12]. These devices offer the possibility of standing and walking, which helps prevent secondary complications and addresses psychosocial issues associated with prolonged wheelchair use [13]. Research indicates that WREs can enable patients with motor-complete SCI to walk in a comfortable and controlled manner, both at home and in the community, by facilitating a reciprocal stepping pattern with both legs.

Robotic Assisted Gait Training (RAGT), employing technologies like exoskeletons and end-effector devices, has emerged as a prevalent neurorehabilitation intervention for stroke survivors and those with spinal cord injuries who struggle with independent ambulation [13]. These interventions yield incremental benefits for motor and functional recovery, facilitating early mobilisation of lower limbs. Moreover, the intensity, duration, frequency, and quality of movement achievable with RAGT surpass those of Conventional or Traditional Gait Training (TGT). While end-effectors apply mechanical forces to distal limb segments, offering ease of setup, they may lack precise control over proximal joint movements, potentially leading to aberrant movement patterns. Conversely, robotic exoskeletons, aligning with the wearer's anatomical axes, afford direct control over individual joints, there by minimising postural or movement abnormalities [14].

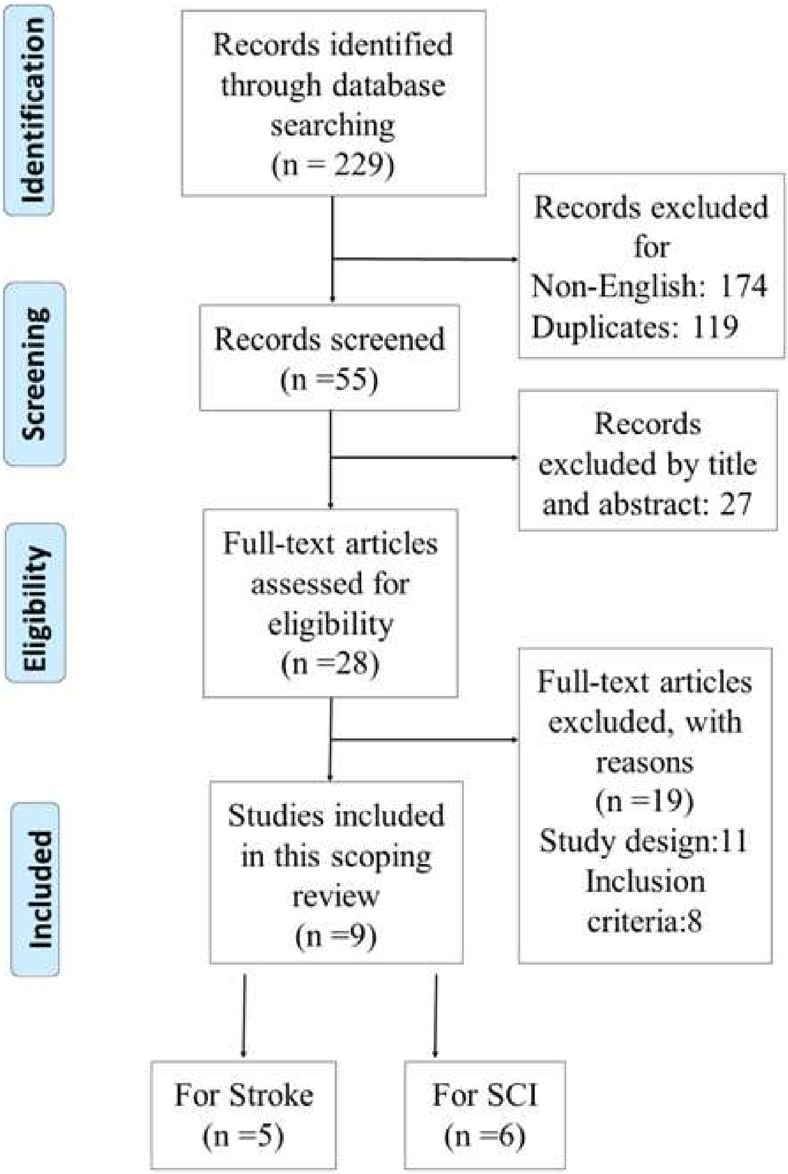
However, it's important to note that while WREs and RAGT offer potential benefits, they may also pose risks, such as skin lesions or bone fractures in the lower limbs. Thus, careful consideration and monitoring of patients during training are essential to minimise adverse events.

Integrating advanced robotic technologies, such as WREs and RAGT, into rehabilitation programs represents a significant advancement in spinal cord injury treatment, offering hope for improved outcomes and enhanced quality of life for affected individuals [15]. Many recommended that the application of robotics in rehabilitation environments be maximised by providing hybrid protocols with other established techniques such as exercise, gait training, and functional electrical stimulation (FES) [16]. Therefore, in this Scoping review, we aimed to assess the efficacy of RAGT in patients with stroke and spinal cord injuries to provide PRM physicians with the state-of-the-art on this crucial topic.

METHODOLOGY

This scoping review aimed to map the current literature surrounding the use of robotic exoskeletons for gait rehabilitation in adults post-stroke. Five databases (SCOPUS, Pubmed, MEDLINE, CINAHL, Cochrane Central Register of Clinical Trials) were searched for articles from January 2015 till date. Reference lists of included articles were reviewed to identify additional studies. Articles were included if they utilized a robotic exoskeleton or end effector robots as a gait training intervention for adult stroke survivors, complete and/or incomplete spinal cord injuries, and reported walking outcome measures. Training periods ranged from single-session to 12-week interventions. The main walking outcome measures were gait speed, Timed Up and Go, 6-min Walk Test, and the Functional Ambulation Category.

Search Strategy: (((((Stroke) OR Spinal cord injury) AND Robotic-assisted gait training) AND Functional Outcome) OR Quality of life) AND Intervention



Pic-1: Flow chart for selection process of studies this scoping review

Scientometric details of studies included stroke and RAGT (n=5)

Authors and Year	Intervention	Comparator	No. of Subjects	Duration	Outcomes
Dennis R. Louie 2021 [17]	Exoskeletal group	Usual care group	EG: 19 UCG: 17	60 min each session, three times a week, max up to 8 weeks	Spatio-temporal parameters of gist, 6MWT
Karen J Nolan 2020 [18]	Robotic exoskeleton gait training	Nil	10	10 sessions	FIM, total distance walked
Michela Goffredo 2019 [19]	Overground Exoskeleton (OE)	End-effector (EE) and Conventional Gait Training (CGT)	OE: 8 EE: 8 CAGT: 10	Each group 13-17 sessions, 3 days a week for 6 weeks	FAC, WHS, 6MWT, 10MWT, TUG, Spatio-temporal gait parameters
Magdo Bartole 2015 [20]	H2 Robotic exoskeleton	Nil	3	18 sessions, in the 4-week period	No of steps per minute, Walking speed, distance, endurance, lower limb muscles
Kota Takahashi 2015 [21]	Proportional Myoelectric Propulsion powered ankle exoskeleton	No exoskeleton, To powered assistance	5	One session with a 15-minute duration	Peak ankle moment EMG, Net metabolic power

Scientometric details of studies included for spinal cord injuries and RAGT (n=6)

Authors and Year	Intervention	Comparator	No. of Subjects	Duration	Outcomes
Angel Gil-Agudo 2023 [22]	HANK exoskeleton	traditional gait training program	12 11	30-60 min each session, 3 sessions each week for 5 weeks	Pain and fatigue through a Visual Analogue Scale. LEMS, WISCI-II, and SCIM-III scales
Sutor T.W. 2022 [23]	EAW with TSS program	EAW without the TSS program	8 3 5	2–3 times per week for 12 3 5weeks.	10MWD and WC and AC), body composition assessment (dual exposure x-ray absorptiometry
Dylan j Edwards 2022 [24]	exoskeleton gait training	standard gait training and No gait training	9 10 6	12 weeks, 36 sessions	Timed-Up-and-Go (TUG), 6-min walk test (6MWT), Walking Index for Spinal Cord Injury (WISCI-II)
Xiao-Na Xiang 2021 [25]	Exoskeleton assisted walking	conventional group	18 9 9	16 sessions of 50–60 min training (4 days/week, 4 weeks).	Forced vital capacity (FVC), forced expiratory volume in 1 s (FEV1), forced expiratory flow (FEF), peak expiratory flow, and maximal voluntary ventilation, 6MWT with assisted devices and LEMS
Nicola Pastol 2021 [26]	free-standing lower limb robotic exoskeleton	na	3	twice weekly for 12 weeks	SCIM-III.
Chung-Ying Tsai 2021 [27]	exoskeletal-assisted walking	na	7	median 30 sessions (range from 7 to 90 sessions)	Computerized dynamic posturography, which provided measurements of endpoint excursion (EPE), maximal excursion (MXE), and directional control (DCL).

RESULTS

Stroke and Robotic Assisted Gait Training: In 2021, Dennis R. Louie et al. conducted a randomised controlled trial assessing the effectiveness of an exoskeleton-based physical therapy program for non-ambulatory patients during subacute stroke rehabilitation. Thirty-six stroke patients were randomly assigned to either the Exoskeleton group (n = 19) or the Usual Care group (n = 17). The

Exoskeleton group underwent 60-minute sessions three times a week for up to 8 weeks, while the Usual Care group received standard physical therapy, typically 4–5 days a week, lasting 45–60 minutes per session, also for up to 8 weeks. Compared to the Usual Care group, significant improvements in gait speed (p=0.04) and the 6-minute walk test (p=0.03) were observed in the Exoskeleton group from discharge to the 6th month follow-up. No significant differences were found within or between the Usual Care group groups for gait speed and the 6-minute walk test. Additionally, no adverse events were reported in the Exoskeleton group. The study concludes that an exoskeleton-based physical therapy program can safely integrate into inpatient stroke rehabilitation for non-ambulatory patients during the subacute phase without detriment [17].

In 2020, Karen J. Nolan et al. conducted a study to assess the feasibility and potential advantages of robotic exoskeleton gait training during acute stroke inpatient rehabilitation. This single-arm pilot study involved 10 participants with acute stroke who received 10 sessions of robotic exoskeleton gait training (RE+SOC) within their inpatient rehabilitation program. The exoskeleton provided adjustable lower limb assistance during walking and gait training. Primary outcomes included the functional independence measure (FIM), including Motor FIM Change, Walk FIM Change, Walk FIM Efficiency, Maximum Distance, Motor FIM Efficiency, and Total Distance during conventional training using the robotic exoskeleton into acute stroke inpatient rehabilitation. Significant differences were observed in the average change in motor FIM within the RE+SOC group. The study also highlighted an improved relationship between total distance walked and the difference in Motor FIM when RE training was integrated into the inpatient stroke rehabilitation program [18].

In a 2019 pilot observational non-randomized controlled trial, Michela Goffredo and colleagues aimed to assess the impacts of End-Effector, Overground Exoskeleton, and Conventional Gait Training on clinical outcomes during acute Stroke Gait Rehabilitation. The study categorised eligible participants into three groups: the end-effector t-RAGT (GG) group (8 subjects), the exoskeleton o-RAGT (EG) group (8 subjects), and the conventional gait training (CG) group (10 subjects). Sessions for the GG group lasted 60 minutes, occurring three days a week for six weeks, with training beginning at a speed of 1.5 km/h and gradually increasing. Similarly, the EG group received comparable sessions with the exoskeleton assisting in leg power. The CG group focused on muscle strengthening, static and dynamic exercises, trunk control, and proprioception. Results showed significant differences in several clinical measures across all groups but not in spatio-temporal gait parameters, indicating a necessity for further investigation into biomechanics and neurophysiological signals concerning gait outcomes [19].

In 2015, Magdo Bortole et al. conducted a clinical study titled “The H2 Robotic Exoskeleton for Gait” to evaluate its early efficacy in stroke rehabilitation. Three chronic stroke participants underwent 18 H2 robotic exoskeleton gait training sessions over six weeks. The exoskeleton offered adjustable lower limb assistance during walking. Primary outcomes included walking speed, distance, endurance, and lower limb muscle strength changes. Results showed increased step count and speed, enhanced distance and endurance, and improved muscle strength. Participants reported high satisfaction and motivation. However, caution is warranted in generalising findings due to the small sample size, limiting the study’s representativeness of the broader stroke population and the ability to draw definitive conclusions about the H2 device’s impact on gait improvement [20].

In 2015, Kota Takahashi et al. conducted a feasibility study on a neuromechanics-based powered ankle exoskeleton for post-stroke walking assistance. Five stroke subjects participated, wearing the Proportional Myoelectric Propulsion (PMP) powered ankle exoskeleton on their paretic limb. They underwent three walking conditions on an instrumented treadmill: without the exoskeleton (NoEXO), with the exoskeleton but without powered assistance (UnPOW), and with powered exoskeleton assistance (POW). Each condition lasted 5 minutes with 5 minutes of rest in between, and the POW condition was repeated three times. Kinematic data (120 Hz) were captured using a motion analysis system, while kinetic data (960 Hz) and EMG outcome variables were collected with the instrumented treadmill during walking trials. Results showed enhanced paretic ankle moment with all three powered conditions compared to NoEXO, approximately 16% greater. Despite this, there was no significant effect on ankle-positive work. The study concluded that the neuromechanics-based powered exoskeleton improved paretic ankle moment during walking in stroke patients [21].

Spinal Cord Injuries and Robotic Assisted Gait Training: In 2023, Ángel Gil-Agudo et al. conducted a randomized controlled trial to evaluate the safety and feasibility of using the HANK exoskeleton for walking rehabilitation and to assess its effects on walking function. Twenty-three subjects were divided into an intervention group (n=12) and a control group (n=11). The intervention group underwent 15 one-hour gait training sessions with the HANK exoskeleton, while the control group received traditional gait training sessions. Pain and fatigue were measured using a Visual Analogue Scale. Outcome measures included LEMS, WISCI-II, SCIM-III, 10MWT, 6MWT, and TUG walking tests. The use of the HANK exoskeleton was found to be safe and well-tolerated. Patients treated with the exoskeleton showed improved walking independence according to the WISCI-II scale after the treatment [22].

In 2022, Sutor T.W et al. conducted an exploratory study on Exoskeleton Training and Trans-Spinal Stimulation for Physical Activity Enhancement After Spinal Cord Injury. Eight participants with chronic SCI were enrolled in an Exoskeleton-Assisted Walking (EAW) program 2–3 times weekly for 12 weeks. Anthropometric measurements (seated and supine waist and abdominal circumferences), body composition assessment (dual-energy X-ray absorptiometry-derived body fat percentage, lean mass, and total mass for the total body, legs, and trunk), and peak oxygen consumption (VO2 during a 6-minute walk test [6MWT]) were evaluated pre- and post-12 weeks of EAW training. A subset of participants (n = 3) underwent EAW training with concurrent Trans-Spinal Stimulation (TSS), and neuromuscular activity of locomotor muscles is assessed during a 10-meter walk test (10MWT) with and without TSS post-12 weeks of EAW training. The study revealed that 12 weeks of EAW can enhance anthropometrics and body composition in non-ambulatory individuals with chronic SCI. These improvements may stem partially from the aerobic exercise facilitated by EAW, although varying aerobic adaptations were noted among participants [23].

In 2022, Dylan J. Edwards et al. conducted a randomized controlled trial to demonstrate the effectiveness of a 12-week exoskeleton-based robotic gait training program in improving independent gait speed among community-dwelling participants with chronic incomplete spinal cord injury (SCI). Twenty-five participants completed the study. The intervention group (n=9) received 12 weeks of exoskeleton gait training comprising 36 sessions, while the standard group (n=10) underwent standard gait training, and the control group (n=6) received no gait training. Post-intervention, the primary outcome was robot-independent gait speed (10-meter walk test, 10MWT). Secondary outcomes included Timed-Up-and-Go (TUG), 6-minute walk test (6MWT), Walking Index for Spinal Cord Injury (WISCI-II), and therapist-reported NASA-Task Load Index. Although raw gait speed improvements were not statistically significant at the group level, the study found that 12 weeks of exoskeleton robotic training improved clinical ambulatory status in participants with chronic SCI who had independent stepping ability at baseline [24].

In 2021, Xiao-Na Xiang conducted a prospective, single-center, single-blinded, randomized controlled pilot study investigating the impact of Exoskeleton-Assisted Walking (EAW) on pulmonary function and walking parameters in individuals with spinal cord injury (SCI).

Eighteen SCI participants were randomly assigned to the EAW group (n = 9) or conventional group (n = 9) and received 16 sessions of 50–60 minutes of training over 4 weeks. Pre- and post-training assessments included pulmonary function parameters such as forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), and 6-minute walk test (6MWT) with assisted devices, along with Lower Extremity Motor Score (LEMS). Significant improvements were observed in FVC ($p = 0.041$), predicted FVC% ($p = 0.012$), and FEV1 ($p = 0.013$) in the EAW group compared to the conventional group post-training. Additionally, participants in the EAW group completed the 6MWT with a median increase of 17.3 meters while wearing the exoskeleton. No adverse events were reported. These findings suggest that EAW may offer potential benefits in enhancing pulmonary function parameters among individuals with lower thoracic neurological levels of SCI compared to conventional training methods, with the additional assistance of a robotic exoskeleton [25].

In 2021, Nicola Pastol et al. conducted a study to assess the feasibility and potential health-related benefits of therapy utilizing a free-standing exoskeleton for individuals with spinal cord injury (SCI). Of 7 subjects, 3 completed all 24 intervention sessions and the subsequent follow-up assessment. This 12-week intervention, followed by a 12-week waitlist control period and a 12-week follow-up, involved providing participants with SCI, scoring < 5 on the mobility section of the spinal cord independence measure (SCIM-III), twice-weekly therapy sessions in the REX (Rex Bionics, Auckland, NZ) robotic exoskeleton for lower limb support. The primary outcome measure was function, assessed using the SCIM-III, with a battery of secondary outcomes included. Participants also completed a survey to gauge their perceptions of this treatment modality. Positive trends were observed in function, fatigue, quality of life, mood, grip and quadriceps strength, lower limb motor function, and percentage of lean body mass in several participants during the intervention phase [26].

In 2021, Chung-Ying Tsai conducted a pre-post intervention pilot study to investigate the potential impact of exoskeletal-assisted walking (EAW) on seated balance among individuals with chronic motor complete spinal cord injury (SCI). Seven participants underwent supervised EAW training using a powered exoskeleton (ReWalkTM) for a median of 30 sessions (ranging from 7 to 90). Seated balance testing outcomes were assessed before and after EAW training using computerized dynamic posturography, measuring endpoint excursion (EPE), maximal excursion (MXE), and directional control (DCL). Following EAW training, significant improvements were observed in total-direction EPE and MXE ($p < 0.01$ and $p < 0.017$, respectively). While improvements are noted in the Modified Functional Reach Test (MFRT) and physical functioning and role limitations due to physical health, these changes did not reach statistical significance. The study suggests that EAW training holds promise in enhancing seated balance for individuals with chronic motor complete SCI [27].

DISCUSSION

Gait training in stroke patients is vital for restoring mobility and independence. Robotic-assisted gait technology enhances this process by providing tailored assistance and feedback. Robotic devices aid in relearning proper gait patterns through precise movements and support. Consistent training with these technologies promotes neuroplasticity, facilitating recovery [28].

The adjustable nature of robotic systems allows for personalized rehabilitation plans catering to individual needs and abilities. Real-time feedback helps stroke patients correct their gait abnormalities, promoting safer and more efficient walking. Robotic-assisted gait training also reduces the physical strain on therapists, enabling them to focus on other aspects of rehabilitation. The repetitive nature of robotic training sessions ensures consistent practice, leading to better outcomes. Engaging in gait training with robotic technology fosters motivation and confidence in stroke patients, encouraging them to strive for further improvemen. Integrating robotic technology into gait rehabilitation programs ultimately empowers stroke patients on their journey toward recovery and improved quality of life [29].

Early recovery and cost reduction are critical goals in stroke and spinal cord injury (SCI) rehabilitation, and technology plays a pivotal role in achieving them. Advanced technologies such as robotic exoskeletons, virtual reality systems, and telemedicine platforms offer innovative solutions to accelerate recovery while minimizing expenses [30].

In early recovery, technology provides immediate access to specialized care through telemedicine consultations and remote monitoring systems, even in remote areas. This early intervention can prevent complications, reduce hospital stays, and facilitate faster progress in rehabilitation [31].

Moreover, technological advancements streamline rehabilitation processes, optimizing resource utilization and minimizing the burden on healthcare systems. Robotic-assisted therapy, for instance, allows for intensive, repetitive training sessions without the need for constant supervision by therapists, thus reducing labor costs and increasing treatment efficiency. Additionally, technology enables personalized rehabilitation plans tailored to each patient's needs, optimizing outcomes while minimizing unnecessary interventions. Virtual reality and gamification techniques make therapy engaging and enjoyable, promoting adherence and enhancing results without incurring additional costs [32].

By integrating technology into stroke and SCI rehabilitation, healthcare providers can achieve early recovery milestones more effectively while reducing the economic burden on patients, caregivers, and healthcare systems. This approach fosters a more sustainable and accessible model of care, ultimately improving outcomes and quality of life for individuals recovering from neurological injuries [33].

In middle-income countries, leveraging technology in stroke and spinal cord injury (SCI) rehabilitation can expedite early recovery and alleviate cost burdens. Telemedicine facilitates timely access to specialized care, reducing hospital stays and associated expenses. Robotic-assisted therapy optimizes resource utilization by providing intensive, personalized rehabilitation without constant supervision. Virtual reality systems enhance therapy effectiveness, promoting adherence and minimizing the need for additional interventions [34]. By integrating these technologies, middle-income countries can enhance rehabilitation outcomes, shorten recovery times, and reduce the economic strain on patients, caregivers, and healthcare systems, thereby improving accessibility to quality care for individuals with neurological injuries [35].

Robotic-assisted gait training presents both challenges and opportunities in neurological conditions.

Challenges:

1. Cost: Robotic devices can be expensive to procure and maintain, limiting access in resource-constrained settings.

2. Training and expertise: Healthcare professionals require specialized training to operate and interpret data from robotic devices effectively.

3. Patient variability: Neurological conditions present diverse motor impairments, requiring customization of robotic interventions to suit individual needs.

4. Technical limitations: Current robotic devices may lack adaptability to accommodate complex gait patterns or severe impairments.

5. Acceptance and motivation: Some patients may resist or struggle to adapt to robotic interventions due to discomfort or lack of motivation.

Opportunities:

1. Enhanced precision: Robotic devices offer precise control over gait parameters, enabling tailored rehabilitation strategies.

2. Intensive, repetitive training: Robotic-assisted gait training allows for high-intensity, repetitive practice, promoting neuroplasticity and functional recovery.

3. Objective assessment: Robotic devices provide objective data on gait performance, facilitating accurate progress monitoring and treatment planning.

4. Accessibility: Technological advances may lead to the development of more affordable and portable robotic devices, expanding access to rehabilitation services.

5. Personalized therapy: Robotic-assisted gait training can be customized based on individual needs, optimizing outcomes and promoting patient engagement.

CONCLUSION

Addressing challenges and leveraging opportunities in robotic-assisted gait training requires collaborative efforts among researchers, healthcare professionals, engineers, and policymakers to develop innovative solutions that enhance the accessibility, affordability, and effectiveness of rehabilitation interventions for individuals with neurological conditions.

ABBREVIATIONS

DCL	Directional Control
EMG	Electromyography
LEMS	Electromyography
EPE	Endpoint Excursion
FEV	Forced Expiratory Volume
FVC	Forced Vital Capacity
FAC	Functional Ambulation Categories
MXE	Maximal Excursion
SCIM	Spinal Cord Independence Measure
TUG	Time Up And Go Test

Authors Contribution

Ninad Saraf: Conception and design, Search Strategy; **Hrishikesh Korada:** Analyzed the data, Search Strategy, Drafting and Writing; **Pragathi Shetkar:** Analyzed the data, Collected the data; **Ranjith Anumasa:** Conception and design, Drafting and Writing.

Conflicts of interest: None

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