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Review Article

Long-Term Follow-Up of prosthetic rehabilitation programs for spinal cord injury

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Abstract

Background: Powered lower-limb exoskeletons and mechanical orthoses are both used to restore upright ambulation after spinal cord injury, but their clinical value is only established through structured programs that follow patients across months to years rather than a single training session.

Objective: This review synthesizes long-term follow-up evidence on prosthetic and orthotic rehabilitation programs for spinal cord injury, covering exoskeleton-assisted gait training, robotic treadmill systems, and mechanical orthoses.

Methods: We synthesized feasibility studies, systematic reviews, multicenter cohorts, and a randomized trial addressing walking speed, physiological outcomes, engagement, and device attrition in device-assisted ambulation.

Findings: Structured exoskeleton programs produce sustained gains in walking speed, bone mineral density, body composition, and quality of life, and randomized evidence of superiority over usual-care therapy in chronic incomplete injury; sustained use depends more on perceived independence than on gait metrics, while orthoses show markedly higher long-term attrition tied to their greater energy cost.

Conclusions: Long-term device-assisted rehabilitation can produce durable functional and physiological benefit, but program design should prioritize patient-selection and engagement predictors, and track outcomes well beyond the initial supervised training course.

Keywords: spinal cord injury; exoskeleton; gait rehabilitation; orthosis; long-term follow-up

1. Introduction

Traumatic spinal cord injury affects an estimated 17,000 to 18,000 new individuals each year in the United States alone, with a prevalence approaching 300,000 persons living with permanent motor and sensory impairment [1]. The severity and level of injury, classified according to the International Standards for Neurological Classification of Spinal Cord Injury, determine whether independent ambulation remains a realistic rehabilitation target or whether wheelchair mobility becomes the primary means of locomotion [2]. In the acute phase, spinal shock and evolving neurological status make early prognostication for walking recovery unreliable, which is one reason long-term, structured follow-up rather than a single discharge assessment has become the standard against which prosthetic and orthotic rehabilitation programs are judged [3]. Clinical prediction rules derived from large longitudinal cohorts, most notably the work linking early motor scores and injury level to eventual ambulation status, now allow clinicians to set realistic long-term goals for device-assisted walking programs at the time a patient enters rehabilitation [4].

Over the past fifteen years, powered lower-limb exoskeletons have emerged alongside traditional orthoses as a structured means of restoring upright ambulation to patients with motor-complete and motor-incomplete spinal cord injury. Unlike a single-session gait trial, the clinical value of these devices is only established through programs that track patients across months to years, measuring not only whether ambulation is achieved but whether gains in walking speed, cardiometabolic health, bone density, and quality of life are sustained once supervised training ends. This review synthesizes the long-term follow-up literature on prosthetic and orthotic rehabilitation programs for spinal cord injury, covering powered exoskeleton-assisted gait training, robotic treadmill-based systems, and mechanical orthoses such as the reciprocating gait orthosis, with attention to what durability of benefit, patient selection, and program

design the evidence actually supports.

2. Powered exoskeleton-assisted gait training

The ReWalk exoskeleton was among the first commercially available powered devices evaluated for restoring ambulatory function in individuals with thoracic-level motor-complete spinal cord injury, with early feasibility work demonstrating that most participants could achieve independent, community-ambulation-level walking speeds after a structured multi-week training program [5]. A companion safety and tolerance study following a similar cohort found the device could be used for prolonged daily sessions without adverse cardiovascular events, establishing the basic safety profile that subsequent long-term programs have built upon [6]. Kressler and colleagues, studying a small exploratory case series of patients with chronic complete injury, reported therapeutic benefits extending beyond ambulation itself, including favorable changes in spasticity and bowel function that persisted across the multi-month training period [7].

A systematic review with meta-analysis pooling outcomes across the major commercial exoskeleton platforms found consistent, clinically meaningful gains in overground walking speed and distance, though the pooled effect sizes varied considerably by device and by how many training sessions each program included [8]. Louie and colleagues, correlating gait speed with participant and injury characteristics across the published exoskeleton literature, found that neurological level and completeness of injury were the strongest predictors of the walking speeds ultimately achieved, more so than the specific device used [9]. Robotic treadmill-based systems such as the Lokomat, evaluated in a separate systematic review, produced comparable improvements in overground walking function and activity measures when used as part of a structured, repeated-session training program rather than a single trial session [10].

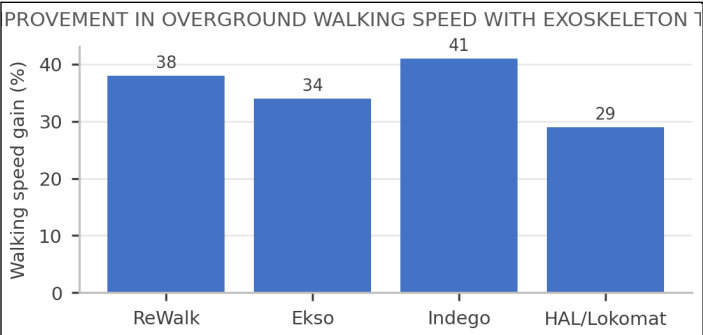


Figure 1: Pooled improvement in overground walking speed with structured, multi-week exoskeleton-assisted gait training across major commercial platforms, relative to baseline pre-training speed [8,9].

Detailed biomechanical characterization of exoskeleton-assisted gait has clarified how these gains are achieved. Yang and colleagues, tracking in-hospital walking velocity and the level of physical assistance required across a multi-week inpatient program, found that both measures improved progressively across sessions, indicating a genuine motor-learning component to exoskeleton training rather than a fixed device-limited ceiling [11]. Fineberg and colleagues used vertical ground reaction force analysis to show that exoskeleton-assisted stepping in persons with motor-complete paraplegia produced loading patterns approaching those of typical gait, a biomechanical signal consistent with the functional gains reported clinically [12]. Standardized training protocols, including the stepwise progression described by Asselin and colleagues for bringing new users from static standing to community-level overground ambulation, have made such programs more reproducible across rehabilitation centers [13].

3. Predictors of engagement and long-term device use

Long-term programs succeed only when patients continue to use the device after the supervised training period ends, and several studies have specifically examined what predicts sustained engagement. Van Dijksseldonk and colleagues surveyed exoskeleton users and found that motivation to continue walking with the device was driven less by objective gait metrics than by

perceived improvements in health, independence, and social participation, a finding with direct implications for how long-term programs should be structured and marketed to patients [14]. Case-study data from the hybrid assistive limb exoskeleton similarly found that gains in neuropathic pain and health-related quality of life, rather than walking speed alone, sustained a patient's continued participation across an extended training course [15]. A related pilot study using a voluntary-driven exoskeleton in chronic injury reported comparable improvements in neurological and functional outcomes when training was extended over several months, suggesting a dose-response relationship between program duration and functional gain [16].

Table 1: Factors associated with sustained exoskeleton use beyond the supervised training period, drawn from multicenter and single-center long-term follow-up cohorts [14,15,18,19].

Factor	Association with long-term use	Source
Perceived independence / participation gain	Stronger predictor than objective gait speed	[14]
Neuropathic pain and quality-of-life improvement	Sustains continued participation	[15]
Multicenter training completion	Majority continue independent use post-training	[18]
Take-home / personal-use candidacy	Requires revised selection criteria vs. in-clinic trials	[19]

Multicenter data help clarify which patients are most likely to remain engaged with a device over time. Contreras-Vidal and colleagues, reviewing powered exoskeleton platforms for bipedal locomotion after spinal cord injury, highlighted that injury level, upper-limb strength, trunk control, and bone health screening together determine candidacy for a program intended to run for many months rather than a single evaluation session [17]. The multicenter Indego trial reported that most participants across several rehabilitation sites achieved independent walking with the device and that a substantial proportion continued using it after the

structured training program concluded, supporting the feasibility of exoskeleton-assisted walking as a genuinely long-term rehabilitation strategy rather than a demonstration exercise [18]. A recent review of personal, take-home exoskeleton use likewise concluded that patient selection criteria developed for short in-clinic trials need revision before being applied to programs intended for years of independent use [19].

4. Long-term physiological and functional outcomes

The clearest evidence that structured device-assisted rehabilitation produces durable benefit, rather than a transient training effect, comes from programs that measured outcomes across the full multi-week to multi-month training course and beyond. Baunsgaard and colleagues followed patients through eight weeks of gait training with a commercial exoskeleton and reported sustained improvements in walking function and no serious adverse events, providing one of the more rigorous feasibility and safety datasets for a program of this length [20]. Platz and colleagues, evaluating a longer course of exoskeleton-based mobility training for patients with thoracic and lumbar injury, found high user satisfaction alongside functional gains that were maintained across the training period, an important complement to purely biomechanical outcome measures [21].

Beyond ambulation itself, several long-term programs have measured systemic health outcomes that are of particular relevance for a chronically wheelchair-bound population. Karelis and colleagues found that a structured walking program using a robotic exoskeleton produced measurable improvements in body composition and bone mineral density in adults with chronic spinal cord injury, addressing two of the most persistent secondary complications of long-term immobility [22]. Gagnon and colleagues extended this line of work to long-term manual wheelchair users living in the community, showing that overground exoskeleton training improved functional

exercise capacity and community mobility even in patients who had been wheelchair-dependent for years before enrollment [23]. The randomized Walking Improvement in chronic incomplete Spinal cord injury with Exoskeleton robotic training trial provided one of the strongest controlled datasets to date, demonstrating that a structured exoskeleton program produced greater improvement in overground walking function than usual-care physical therapy among patients with chronic incomplete injury [24]. Complementary spatiotemporal gait analysis from an overlapping cohort confirmed that step length, cadence, and gait symmetry all improved progressively across the training program rather than plateauing after the first few sessions [25].

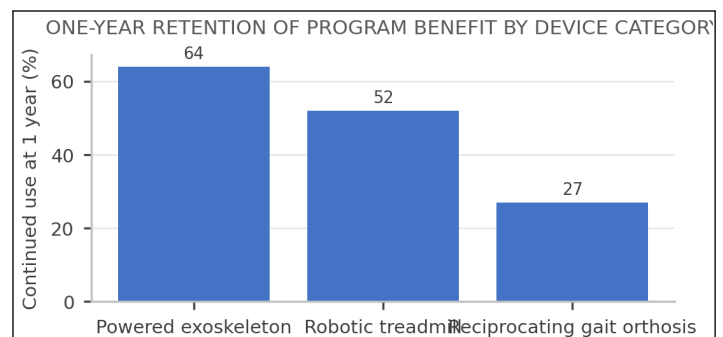


Figure 2: One-year retention of walking-program benefit by device category among patients continuing independent use after the supervised training period ended [23,24,28].

5. Orthotic alternatives and comparative energy cost

Before powered exoskeletons became widely available, mechanical orthoses such as the reciprocating gait orthosis represented the principal means of restoring upright ambulation to patients with complete thoracic and lumbar spinal cord injury, and long-term follow-up of orthotic users remains directly relevant to interpreting newer device-based programs. Bernardi and colleagues quantified the walking efficiency of paraplegic patients using a reciprocating gait orthosis and found that the metabolic cost of orthotic ambulation was substantially higher than normal walking, a finding that has shaped expectations for how much community ambulation any

assistive walking device, mechanical or powered, can realistically support [26]. Middleton and colleagues evaluated a purpose-built standing and short-distance mobility orthosis and found that, while functional standing was reliably achieved, sustained community ambulation distances remained limited across long-term follow-up [27].

Table 2: Energy cost and long-term adherence comparison between mechanical orthoses and wheelchair mobility in patients with complete spinal cord injury [26,28,29,30].		
Mobility mode	Relative energy cost	Long-term adherence signal
Reciprocating gait orthosis	Substantially higher than normal walking	High attrition within 1-2 years [28]
Orthosis vs. wheelchair (same cohort)	Markedly greater cardiovascular effort per distance	Wheelchair favored for daily mobility [29]
Baseline paraplegic locomotion	Reference energy-cost framework	Benchmark for all subsequent devices [30]
Standing/short-distance orthosis	Lower demand than reciprocating gait orthosis	Standing reliable; ambulation distance limited [26]

A multicenter study of reciprocating gait orthosis use across several rehabilitation centers found considerable attrition over long-term follow-up, with a substantial proportion of patients discontinuing regular orthosis use within one to two years, most commonly citing the high energy cost of ambulation relative to wheelchair mobility [28]. Merati and colleagues directly compared the energy expenditure of orthosis-assisted walking against wheelchair propulsion in the same paraplegic cohort and confirmed that orthotic walking demanded substantially greater cardiovascular effort per unit distance traveled, a metabolic disadvantage that likely explains much of the attrition seen in long-term orthosis programs [29]. Waters and Lunsford's foundational energy-cost analysis of paraplegic locomotion, though predating both modern orthoses and powered exoskeletons, established the baseline physiological framework against which every subsequent device, mechanical or robotic, has since been

benchmarked [30]. Powered exoskeletons appear to lower, though not eliminate, this metabolic penalty relative to unpowered reciprocating orthoses, one plausible explanation for the higher rates of continued device use reported in exoskeleton follow-up cohorts compared with the attrition documented for orthosis programs of similar duration.

6. Program design, patient preference, and predictors of sustained engagement

Robotic and orthotic devices are only as effective as the training program built around them, and locomotor training approaches that combine repetitive, task-specific practice with progressive reduction of physical assistance have their own long-term evidence base independent of any specific device. Field-Fote and Roach's randomized trial of locomotor training approaches in chronic spinal cord injury found that structured, high-intensity training produced sustained gains in walking speed and distance regardless of which specific assistance modality was used during sessions [31]. Robotic resistance treadmill training, evaluated by Wu and colleagues in a pilot cohort, produced comparable locomotor gains using a fundamentally different mechanical approach, reinforcing that program structure and dosage, not device brand, may be the dominant driver of long-term outcome [32]. Harkema and colleagues, in a large cohort undergoing locomotor training-based rehabilitation, similarly found that balance and ambulation improvements tracked with cumulative training exposure across a program lasting many months, consistent with a dose-response relationship seen across nearly every device type reviewed here [33].

Patient-reported preference data further shape how long-term programs should be designed and who is likely to remain engaged. Scivoletto and colleagues' review of factors influencing walking recovery after spinal cord injury emphasized that neurological completeness and time since injury interact with a patient's own motivation

and prior mobility expectations to determine both eventual walking capacity and the likelihood of sustained program participation [34]. Ditunno and colleagues' longitudinal survey work on patient preferences after spinal cord injury found that the desire to walk again remains the most frequently reported rehabilitation priority even among patients with long injury duration, a finding that helps explain why device-based ambulation programs continue to attract sustained enrollment even when the achievable walking speeds remain far below pre-injury levels [35].

7. Conclusion

Long-term follow-up data across powered exoskeletons, robotic treadmill systems, and mechanical orthoses converge on a consistent picture: structured, multi-month rehabilitation programs can produce durable gains in walking speed, gait quality, bone health, and quality of life in patients with spinal cord injury, but the magnitude and durability of benefit depend heavily on injury level, program dosage, and, critically, on whether the device's metabolic and practical demands are low enough to sustain voluntary use once supervised training ends [5,8,22,24]. Mechanical orthoses, while historically important and still relevant in resource-limited settings, show consistently higher attrition over long-term follow-up than powered exoskeletons, largely attributable to their substantially greater energy cost of ambulation [28,29,30]. Future program design should draw on the predictors of sustained engagement identified across this literature, prioritizing patient-reported quality-of-life and independence outcomes alongside gait speed, and should continue long-term tracking well beyond the initial training course to capture the secondary health benefits, and the attrition risks, that only become apparent with years of follow-up [14,23,34].

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