

Review Article



# State-of-the-Art in Robotic Rehabilitation for Spinal Cord Injury Patients: A Literature Review

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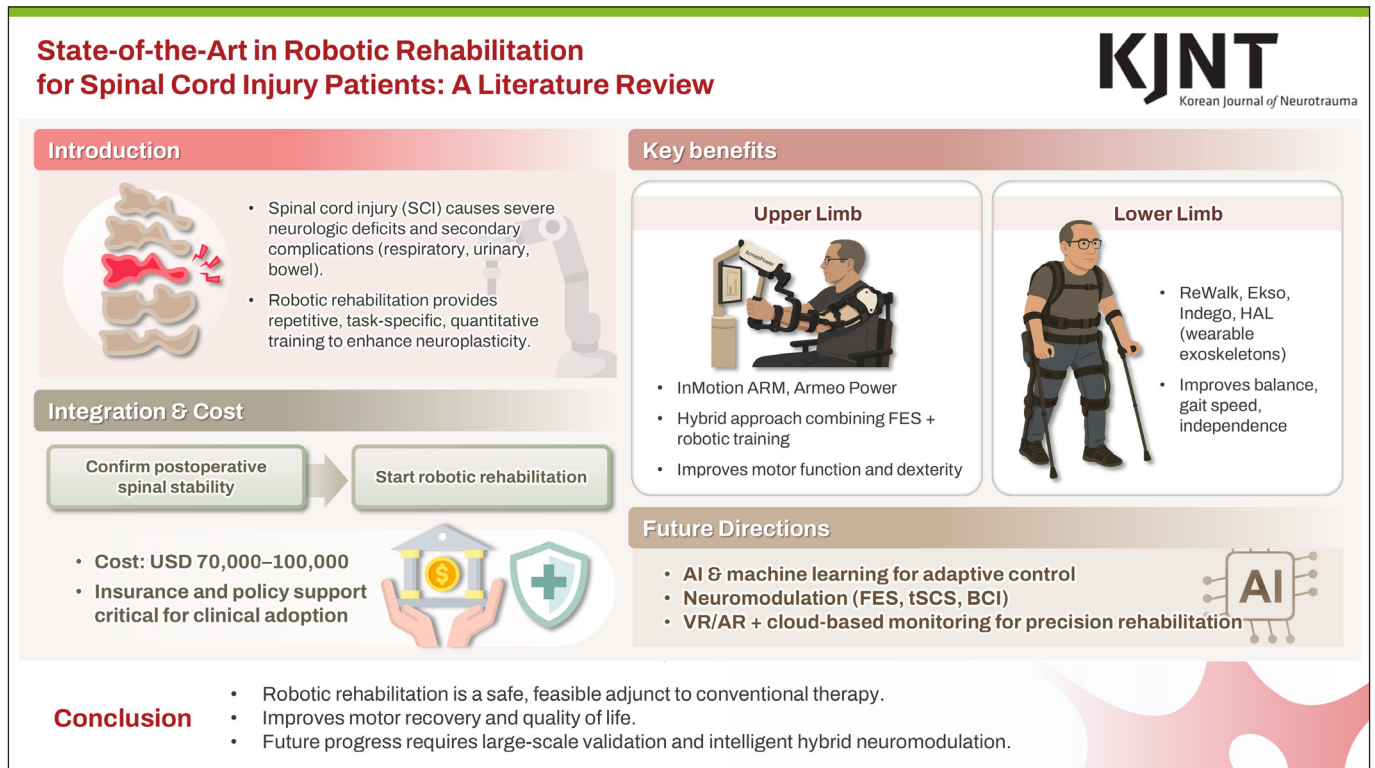
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## ABSTRACT

Spinal cord injury (SCI) causes severe motor, sensory, and functional impairments, often leading to long-term disability. Conventional rehabilitation is labor-intensive and resource-demanding, whereas robotic rehabilitation enables repetitive, task-specific, and intensive training that promotes neuroplasticity. Evidence from clinical and randomized studies shows that upper limb robotic systems, including end-effector and exoskeleton types, improve motor outcomes, especially in the subacute phase. Moreover, hybrid approaches that integrate functional electrical stimulation or spinal cord stimulation appear to provide additional benefits. For lower extremity rehabilitation, ambulatory exoskeletons such as ReWalk, Ekso, Indego, HAL, Rex, Arke, and HANK have been demonstrated to offer safe and feasible gait training, with reported improvements in walking independence, balance, and stride parameters, although enhancements in gait speed remain modest. Preliminary evidence also suggests that exoskeleton-assisted walking may positively influence bowel and urinary function; however, current data are limited. Overall, robotic rehabilitation appears to be a safe and feasible adjunct to conventional therapy, offering moderate improvements in motor function and quality of life in patients with SCI. Nevertheless, further high-quality clinical trials and the integration of neuromodulatory techniques are required to more clearly establish its efficacy and define its role in routine clinical practice.

**Keywords:** Spinal cord injuries; Rehabilitation; Exoskeleton device; Robotics; Dependent ambulation

## GRAPHICAL ABSTRACT



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## INTRODUCTION

Spinal cord injury (SCI), manifesting as complete or incomplete paraplegia or tetraplegia, represents one of the most devastating conditions in neurology and trauma medicine.<sup>13,39,62</sup> Such injuries often lead to irreversible impairments of motor and sensory function, resulting in severe lifelong disability.<sup>62</sup> Beyond the primary neurological deficits, individuals with SCI are also highly vulnerable to a wide range of secondary complications, including recurrent pneumonia, severe pressure ulcers, and recurrent urinary tract infections, all of which contribute substantially to morbidity and mortality.<sup>13,50</sup>

According to a recently published meta-analysis, the global incidence of traumatic spinal cord injury (TSCI) is estimated at 26.5 per million people, whereas the incidence of non-TSCI is 17.9 per million.<sup>39</sup>

Between January 2008 and December 2020, a total of 30,979 newly diagnosed TSCI patients were identified in South Korea, with surgical treatment showing a steady increase over the study period.<sup>50</sup>

Despite considerable advances in acute management, surgical techniques, and rehabilitation strategies over recent decades, SCI continues to be associated with poor long-term outcomes.<sup>13,62</sup> Conventional rehabilitation approaches, particularly gait training, remain labor-intensive, resource-demanding, and limited in intensity and reproducibility. Consequently, SCI imposes not only a heavy personal burden on affected individuals and

their families but also a significant socioeconomic impact on healthcare systems and society at large.<sup>13,66)</sup>

To improve the quality of life of patients with SCI and to enhance their overall contribution to society, effective rehabilitation is essential. Robotic exoskeletons can provide repetitive, task-specific, and intensive gait training, which may enhance neuroplasticity and promote functional recovery. Nevertheless, clinical evidence regarding their efficacy remains heterogeneous and inconsistent, emphasizing the need for a comprehensive review of their applications, benefits, and limitations.

UPPER EXTREMITY REHABILITATION DEVICES

Although much attention has historically been given to gait restoration, recovery of upper-limb function is equally critical, particularly in cervical SCI patients, for whom arm and hand function are pivotal for independence.<sup>2,14,19,45,59)</sup> In cases of upper limb paralysis due to SCI, the recovery of fine motor function, particularly below the wrist, represents the most important therapeutic goal.<sup>45)</sup>

Conventional upper limb rehabilitation, although effective, is labor-intensive, therapist-dependent, and limited in providing the high-intensity, repetitive, and task-specific training required to maximize neuroplastic recovery.<sup>8,36)</sup> In recent years, robotic rehabilitation devices have emerged as promising tools to augment conventional therapy, offering precise, reproducible, and intensive practice of upper extremity movements.<sup>34,44)</sup>

End-effector devices (e.g., InMotion ARM) and exoskeleton-based systems (e.g., Armeo) are the most commonly studied (TABLE 1).<sup>12,32,57)</sup> End-effector systems provide task-oriented, multidirectional movements, while exoskeletons allow for joint-specific control and greater kinematic precision.

TABLE 1. Comparison of upper extremity exoskeletons

| Devices      | Type         | Working principles                                       | Imaging (generated using ChatGPT)                                                     |
|--------------|--------------|----------------------------------------------------------|---------------------------------------------------------------------------------------|
| InMotion ARM | End-effector | Guide hand trajectory for task-based training.           |  |
| Armeo Power  | Exoskeleton  | Joint-specific actuation for shoulder, elbow, and wrist. |  |

A single-blinded randomized controlled trial compared an end-effector robot (InMotion) with an exoskeleton robot (Armeo) in patients with moderate-to-severe upper limb impairment.<sup>34)</sup> Over 4 weeks, both groups received equal therapy doses combining robot-assisted and conventional occupational therapy.<sup>34)</sup> While both interventions led to improvements, the end-effector group showed significantly greater gains in activity and participation, whereas impairment-level measures improved similarly in both groups.<sup>34)</sup> These findings suggest that simpler, impairment-based, high-repetition training with end-effector robots may be more suitable for patients with greater deficits, while exoskeleton robots may be better suited for those with milder impairments. Nonetheless, additional research involving patients with mild-to-moderate upper extremity impairment and employing number-matched training sessions is needed.

Robotic-assisted training, including both exoskeleton-based and end-effector devices, has demonstrated improvements in upper limb motor scores and functional independence measures.<sup>12,31)</sup> While improvements have been reported in chronic SCI and, to a lesser degree, in acute cases, current evidence indicates that robotic-assisted training yields the most pronounced effects when commenced in the subacute stage, a period associated with enhanced neuroplasticity and rehabilitation responsiveness.

Recently, there have been attempts to restore upper extremity function in SCI patients by combining functional electrical stimulation and robotic exoskeletons within a hybrid control framework.<sup>14)</sup> In experiments with healthy individuals, the hybrid controller significantly reduced exoskeleton power consumption while maintaining good trajectory tracking.<sup>14)</sup> This hybrid approach shows promise in lowering energy demands, a key factor for future portable assistive devices, though further refinement is needed to ensure accurate tracking in complex multi-joint movements.

Another study investigated the effects of cervical transcutaneous spinal stimulation on upper limb responses by combining surface electromyography with torque measurements from the MAHI Exo-II exoskeleton in healthy participants.<sup>42)</sup> Rostral stimulation sites activated proximal motor pools (biceps, triceps) at lower thresholds and produced stronger torque responses in proximal joints, while caudal stimulation did not selectively enhance distal responses.<sup>62)</sup> These results emphasized the need for individualized stimulation strategies.

Furthermore, a randomized clinical trial assessed whether combining cervical transcutaneous spinal cord stimulation (tSCS) with robotic exoskeleton training (Armeo®Power) could enhance upper limb recovery in patients with subacute cervical SCI.<sup>19)</sup> Twenty-two participants underwent either exoskeleton training alone or in combination with tSCS over 8 sessions in 2 weeks. Both groups improved in strength, dexterity, and, but the combined group achieved greater gains in GRASP strength, prehension ability, and grip force.<sup>19)</sup> These findings suggest that adding cervical tSCS to robotic training may provide additional functional benefits and support the potential of hybrid neuromodulation–robotic strategies for optimizing rehabilitation outcomes.

Robotic devices deliver consistent, repetitive, and task-specific practice, which is essential for activity-dependent neuroplasticity.<sup>15)</sup> By enabling repetitive reaching, grasping, and manipulation tasks, robots facilitate sensory-motor integration and strengthen spared corticospinal and propriospinal pathways.<sup>45)</sup> Assist-as-needed algorithms promote active engagement and thereby optimize motor learning. Moreover, robotic rehabilitation alleviates

therapist workload while enabling objective quantification of kinematic and kinetic performance, thus supporting individualized treatment adjustments. With the advancement of hybrid systems that integrate neuromodulation and robotics, there is substantial potential to achieve more effective upper limb rehabilitation outcomes in patients with SCI.

## LOWER EXTREMITY REHABILITATION DEVICES

In SCI, one of the most disabling consequences is the complete or partial paralysis of the lower limbs.<sup>24)</sup> Accordingly, restoration of ambulation is considered one of the highest priorities in the rehabilitation of individuals with SCI.<sup>64,65)</sup> Rehabilitation strategies aimed at improving walking ability after SCI focus on harnessing neuroplasticity while simultaneously enhancing the strength of the remaining active muscles and optimizing functional compensatory strategies.<sup>6,20,64)</sup>

Intensive gait training can activate the neural circuits known as central pattern generators, which generate rhythmic motor activity.<sup>53,60)</sup> When such activation is sustained for a sufficiently long period in patients with incomplete SCI, it can induce plastic changes not only at the spinal level but also within the motor-sensory cortex.<sup>40)</sup> Furthermore, repetitive and task-specific training simultaneously activates sensory and motor pathways, thereby selecting and strengthening spinal circuits and enhancing the ability to successfully perform trained movements.<sup>26)</sup>

The primary goals of rehabilitation therapy are to minimize the risk of secondary complications such as pressure ulcers, pulmonary and urinary tract infections, osteoporosis, and joint contractures.<sup>29,49)</sup> In addition, restoration of limb mobility aims to improve patients' quality of life and extend life expectancy.

In this context, ambulatory robotic exoskeletons have recently been introduced to provide gait-specific training that closely resembles natural walking.<sup>51)</sup> These devices are primarily targeted toward patients with incomplete SCI who retain the potential for functional recovery.<sup>16,61)</sup> Robotic exoskeletons offer patients optimal challenges in balance and motor control while simultaneously delivering visual and functional feedback aligned with gait performance.

The safety and comfort of exoskeleton robots in both acute and chronic SCI patients have been demonstrated in multiple studies, showing that they enable safe ambulation with lower energy expenditure compared to passive orthoses.<sup>46,56)</sup> Although the stability and technological maturity of these devices continue to improve, their clinical application remains limited.

According to one study, lower extremity rehabilitation devices can be classified into 3 generations.<sup>23)</sup> The first generation consists of weight-reducing exoskeleton robots, the second generation comprises gait-assisted exoskeleton robots capable of overground walking, and the third generation includes intelligent powered exoskeleton robots that integrate advanced technologies such as artificial intelligence, augmented reality, virtual reality, and the Internet of Things, thereby providing assisted walking in combination with enhanced functional capabilities. At present, third-generation robots are still under on-going state, and only limited results have been reported to date.

Several lower limb exoskeletons have been developed and extensively reported in the literature to date, including Lokomat, ReWalk, Ekso, Indego, HAL, Rex, Arke, and HANK (FIGURE 1, TABLE 2).

The Lokomat (Hocoma, Volketswil, Switzerland) is one of the most widely used robotic-assisted gait training (RAGT) devices for individuals with neurological impairments, including SCI.<sup>27)</sup> As a representative first-generation exoskeleton, it is a treadmill-based,



**FIGURE 1.** Images of lower extremity exoskeleton devices. (A) Lokomat, (B) ReWalk, (C) Ekso, (D) Indego, (E) HAL, (F) Rex. As both Arke and HANK currently exist only as prototypes, imaging data could not be included. All images were generated using ChatGPT.

**TABLE 2.** Comparison of lower extremity exoskeletons

| Devices | Type                                      | Actuation                   | Clinical application                      | Key features                                               | Limitations                                                   |
|---------|-------------------------------------------|-----------------------------|-------------------------------------------|------------------------------------------------------------|---------------------------------------------------------------|
| Lokomat | 1st generation, treadmill-based           | Robot-assisted + treadmill  | SCI, brain injury, cerebral palsy         | Widely used stationary gait trainer, body weight support   | Not portable, very expensive                                  |
| ReWalk  | 2nd generation, wearable                  | Motorized                   | SCI, brain injury                         | Usable at home & community                                 | Requires upper limb support (crutches), limited walking speed |
| Ekso    | 2nd generation, wearable                  | Motorized                   | SCI, stroke                               | Widely used in hospitals, supports multiple gait patterns  | Limited personal use, relatively heavy                        |
| Indego  | 2nd generation, wearable                  | Motorized                   | SCI, stroke                               | Lightweight, modular, adjustable powered/passive modes     | Requires upper limb support, limited speed                    |
| HAL     | 2nd generation, wearable                  | EMG-based + motorized       | SCI, brain injury, neuromuscular diseases | Intention-driven control (EMG signals), broad applications | Complex donning process, very expensive                       |
| Rex     | 2nd generation, wearable, self-supporting | Motorized, joystick control | SCI, muscular dystrophy                   | Stable posture without crutches, hands remain free         | Large and heavy, slow mobility                                |
| Arke    | 2nd generation, wearable                  | Motorized                   | SCI                                       | Lightweight, modular                                       | Limited clinical evidence                                     |
| HANK    | 2nd generation, wearable                  | Motorized                   | SCI, stroke                               | Lightweight                                                | Limited clinical evidence                                     |

SCI: spinal cord injury, EMG: electromyography.

driven-gait orthosis that integrates an adjustable body weight support system with robotic actuators at the hip and knee joints.<sup>30)</sup> By guiding the patient's lower limbs through a predefined gait pattern, the device facilitates intensive, repetitive, and task-specific locomotor training in a safe and controlled environment.<sup>4)</sup> A systematic review and meta-analysis of 10 randomized controlled trials involving 502 participants reported that RAGT with the Lokomat significantly improved walking distance, lower limb strength, and functional mobility in patients with acute incomplete SCI compared with conventional overground training.<sup>48)</sup> In contrast, another systematic review and meta-analysis of 21 randomized controlled trials with 709 participants evaluated the Lokomat for lower limb rehabilitation and found that, while it appears effective in improving balance function, it has not demonstrated superiority over conventional therapy in motor recovery, gait speed, or functional independence, underscoring the need for further research.<sup>68)</sup>

The ReWalk (ReWalk Robotics, Yokneam Illit, Israel) is a wearable, powered robotic exoskeleton designed to enable individuals with lower limb paralysis, such as those with SCI, to perform upright mobility.<sup>70)</sup> It is an overground, ambulatory exoskeleton that provides powered hip and knee motion to facilitate walking, standing, sitting, and stair climbing.<sup>17)</sup> Clinical studies have demonstrated that ReWalk can improve walking ability in individuals with paraplegia due to SCI, particularly in community and home environments.<sup>63)</sup> Classified as a second-generation exoskeleton, ReWalk enables overground walking with a gait pattern that more closely resembles natural locomotion compared with treadmill-based systems.<sup>38)</sup> It requires sufficient upper body strength and use of crutches for stability. The initial study published in 2012 demonstrated that the ReWalk exoskeleton enabled individuals with thoracic-level complete SCI to safely stand, transfer, and walk short distances following training.<sup>17)</sup> In addition, participants reported secondary health and psychosocial benefits, supporting ReWalk as a feasible option for rehabilitation.

The Ekso (Ekso Bionics, San Rafael, CA, USA) is classified as a second-generation exoskeleton.<sup>23)</sup> It is a wearable, powered robotic device designed to provide overground gait assistance for individuals with neurological impairments, including SCI and stroke.<sup>33)</sup> The system enables walking, standing, sitting, and transfers through powered hip and knee joints, while users maintain balance with the aid of crutches or a walker.<sup>11)</sup> Training parameters such as step length, walking speed, and assistance level can be individually adjusted to optimize rehabilitation. In 2013, a pilot study involving individuals with SCI evaluated the safety and feasibility of the Ekso exoskeleton in 8 participants with

complete thoracic SCI.<sup>33)</sup> The study reported no major adverse events and demonstrated progressive increases in walking time and speed across training sessions, suggesting that Ekso is safe for supervised clinical use and holds promise for enhancing mobility in individuals without voluntary lower limb function.

The Indego (Parker Hannifin, Cleveland, OH, USA) is also classified as a second-generation exoskeleton.<sup>23)</sup> It is a lightweight, modular powered system (12 kg) equipped with 4 motors that actuate the hip and knee joints in the sagittal plane and incorporates built-in ankle-foot orthoses to enhance stability.<sup>22)</sup> The device consists of 5 quick-connect segments for easy donning, doffing, transport, and storage, and is powered by a rechargeable battery housed in the hip module.<sup>22)</sup> Indego enables sitting, standing, walking, and smooth postural transitions, which are controlled through user-initiated shifts in the center of pressure with the support of a stability aid, while a Bluetooth-connected application allows clinicians to adjust gait parameters and monitor performance in real time.<sup>22)</sup> In a pilot study published in 2015, 16 participants with SCI were evaluated, showing that individuals with tetraplegia walked at slower speeds and required assistance, those with upper paraplegia demonstrated limited potential for community ambulation, and participants with lower paraplegia achieved the highest walking speeds (up to 0.45 m/s) and distances (121 m in 6 minutes), approaching the threshold for community ambulation.<sup>22)</sup>

The HAL (Hybrid Assistive Limb; Cyberdyne Corporation, Tsukuba, Japan) is a second-generation exoskeleton and among the first to integrate voluntary control signals from the user's nervous system with robotic actuation, thereby enabling both rehabilitation and assistive walking.<sup>58)</sup> Evidence from multiple studies has demonstrated that HAL training can improve walking speed, stride length, and balance in individuals with SCI as well as in stroke patients.<sup>1,43,47)</sup> By coupling voluntary neural signals with robotic assistance, HAL is designed not only to facilitate ambulation but also to promote motor recovery through activity-dependent neuroplasticity. In contrast to exoskeletons that primarily rely on weight shifting and the use of crutches (e.g., ReWalk, Ekso, Indego), HAL emphasizes neuro-control as a core mechanism for rehabilitation.

The Rex (Rex Bionics, Auckland, New Zealand) is a hands-free, self-supporting device that differs from ReWalk, Ekso, and Indego by enabling gait training without the need for crutches or a walker.<sup>3)</sup> In the RAPPER II trial involving 20 patients with SCI, all participants were able to transfer into the device, most achieved autonomous control, and 19 successfully performed upper-body exercises while standing.<sup>7)</sup> The majority also completed Timed Up and Go tests with modest assistance, and no serious adverse events were reported.<sup>7)</sup> Although Rex provides slower gait speed compared with ReWalk, Ekso, and Indego, its self-stabilizing design and unrestricted upper-limb use may contribute to higher patient satisfaction.<sup>7)</sup>

The Arke (Bionik Laboratories, Toronto, Canada), similar to the Rex, is a robotic lower-limb exoskeleton designed to enable hands-free balance.<sup>18,35)</sup> Although a study in patients with complete SCI have reported that Arke exoskeleton training is feasible in a clinical rehabilitation environment, the device has thus far remained primarily in the development and clinical testing phase, with fewer large-scale clinical trials compared to ReWalk, Ekso, or Indego.

The HANK (Gogo Mobility Robots SA, Abadiño-Zelaieta, Spain) is an updated version of the Exo-H2 exoskeleton.<sup>20)</sup> In a randomized controlled trial conducted in 2023 involving 23 patients with incomplete SCI of less than one year in duration, its safety and feasibility

for gait training were demonstrated.<sup>20)</sup> Unlike most exoskeletons that lack active ankle actuation, HANK provides full joint actuation, including the ankle.<sup>20)</sup> The guidance force can be modulated as a percentage, ranging from 100% (rigid position control) to 0% (free movement), allowing clinicians to tailor the level of assistance to individual patient capacity and thereby potentially optimize therapeutic outcomes.<sup>20)</sup> Nevertheless, the device remains in a relatively early stage of development, and additional large-scale clinical trials and independent investigations are required to confirm its efficacy, safety, and impact on patient satisfaction.

Although various exoskeletons have been introduced, a recent meta-analysis found that RAGT and conventional physical training yielded comparable effects on walking speed and distance in patients with SCI.<sup>37)</sup> RAGT improved walking stability, independence, motor scores, and respiratory function, while conventional physical training showed superior effects on walking speed in chronic patients beyond 6 months post-injury.<sup>37)</sup> Therefore, RAGT is beneficial for enhancing balance, lower limb function, and respiratory capacity in SCI patients, while a combined approach with conventional therapy is recommended to improve walking speed and distance.

## BOWEL AND URINARY FUNCTION

Impairments in bowel and urinary function are closely linked to reduced quality of life in individuals with SCI. While there are currently no reports of direct robotic rehabilitation targeting these autonomic functions, several studies have investigated the effects of RAGT on bowel and urinary outcomes.<sup>5,25,67)</sup>

A pilot randomized clinical trial evaluated the impact of RAGT on bowel function and gut microbiota in patients with motor-complete SCI.<sup>25)</sup> Sixteen participants were randomized to receive either RAGT with the exoskeleton or conventional rehabilitation for 8 weeks.<sup>25)</sup> Compared with controls, the RAGT group demonstrated modest improvements in bowel management, including increased evacuation frequency, reduced reliance on glycerol enemas, and a downward trend in neurogenic bowel dysfunction scores. Moreover, gut microbiota analysis revealed beneficial compositional shifts, with increased abundance of genera such as *Faecalibacterium*, *Bifidobacterium*, and *Ralstonia*, the latter significantly higher than in controls.<sup>25)</sup> These findings suggest that RAGT may enhance bowel function through modulation of the brain–gut axis, highlighting its potential as a therapeutic strategy for neurogenic bowel dysfunction in SCI.

Another randomized pilot trial investigated the feasibility of RAGT using either the Ekso or Lokomat systems to improve lower urinary tract (LUT) function in patients with motor-complete SCI.<sup>67)</sup> Six participants were enrolled, with 4 allocated to Ekso and 2 to Lokomat training, each completing up to 36 sessions over 12 weeks. The intervention was feasible, with good adherence, minimal adverse events, and successful participant recruitment. Electromyographic recordings showed greater pelvic floor muscle activity during Ekso walking compared with Lokomat training, likely due to the increased trunk engagement required in overground walking.<sup>67)</sup> However, LUT outcomes assessed by urodynamic studies, bladder diaries, and quality-of-life questionnaires were variable and did not show consistent improvements.<sup>67)</sup> These results indicate that while exoskeleton training is feasible and can elicit pelvic floor muscle activity even in motor-complete SCI, its specific effects on LUT function remain uncertain and warrant larger, stratified trials.

Although current evidence remains limited, these pilot studies underscore the emerging potential of robotic rehabilitation to influence autonomic outcomes in SCI. As robotic rehabilitation becomes more widely implemented, future research is expected to further clarify its role in improving bowel and urinary function, thereby providing stronger evidence to guide clinical practice.

In addition to bowel and urinary function, emerging evidence indicates potential benefits of RAGT on respiratory and cardiovascular fitness, primarily through enhanced upright posture and repetitive aerobic activity.<sup>52,69)</sup> Regular exoskeleton-assisted walking may improve pulmonary function and circulation, thereby contributing to overall cardiometabolic health in chronic SCI patients.

## INTEGRATION WITH SURGICAL CONSIDERATIONS AND MULTIDISCIPLINARY CARE

From a neurosurgical perspective, robotic rehabilitation must be integrated with postoperative spinal stability and fusion status, as the safety and feasibility of exoskeleton-assisted training depend on the mechanical integrity of spinal fixation constructs. Establishing an integrated care pathway linking surgical stabilization, radiographic verification of hardware integrity, and stepwise robotic rehabilitation is imperative. Exoskeleton training should begin once patients are medically stable and able to tolerate upright loading, and pilot studies have demonstrated its safety and potential benefits, including improvements in cardiorespiratory and urinary function.<sup>10,41)</sup> Furthermore, meta-analyses indicate that RAGT can improve respiratory function, supporting a well-timed, structured transition from surgical intervention to robotic rehabilitation.<sup>37)</sup> Close collaboration between spine surgeons and rehabilitation specialists is essential to minimize implant-related risks and optimize the timing of robotic intervention.

## COST-EFFECTIVENESS AND INSURANCE COVERAGE

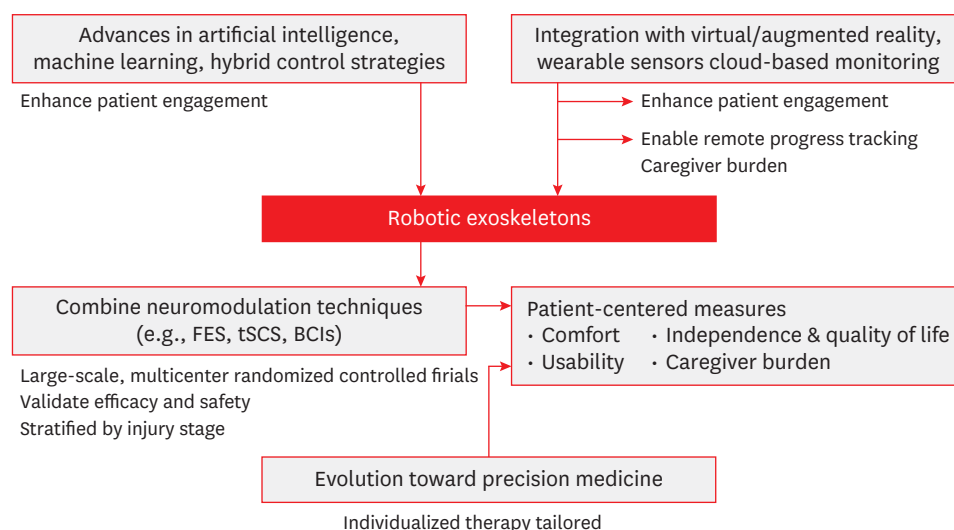
The high cost of robotic exoskeletons remains a major barrier to widespread adoption.<sup>55)</sup> Current market prices for systems such as ReWalk, Ekso, and HAL range from approximately USD 70,000 to 100,000, excluding additional expenses for maintenance and calibration. In South Korea, no published evidence supports routine insurance reimbursement, reflecting the absence of established coverage policies in both public and private sectors. Economic evaluations are therefore required to determine long-term cost-effectiveness, considering potential gains in independence, reduced caregiver burden, and fewer secondary complications. Existing analyses have reported an incremental cost-utility ratio of USD 12,353 per quality-adjusted life year for overground robotic training in complete SCI patients,<sup>55)</sup> and budget impact models suggest potential annual savings of USD 1,000–5,000 with partial integration of robotic sessions.<sup>54)</sup> Nevertheless, the evidence base remains limited, and comprehensive long-term models are needed.<sup>9)</sup> Governmental policy support and cost-sharing mechanisms could facilitate broader clinical adoption.

## FUTURE DIRECTIONS OF ROBOTIC REHABILITATION

Future development of robotic exoskeletons will likely be driven by advances in artificial intelligence, machine learning, and hybrid control strategies that combine neuromodulation techniques such as functional electrical stimulation, tSCS, or brain–computer interfaces.<sup>21,28)</sup> Integration with virtual/augmented reality, wearable sensors, and cloud-based monitoring systems may enhance patient engagement, enable remote progress tracking, and support data-driven optimization of therapy. Beyond functional outcomes, future studies should prioritize patient-centered measures including comfort, usability, independence, quality of life, and caregiver burden. Large-scale, multicenter randomized controlled trials stratified by injury stage are essential to validate efficacy and safety, while cost-effectiveness analyses and policy support will be necessary for widespread clinical adoption. Ultimately, robotic rehabilitation is expected to evolve toward precision medicine, delivering individualized therapy tailored to the neurological and functional profile of each patient (**FIGURE 2**).

## CONCLUSION

Robotic rehabilitation for upper and lower limb recovery in SCI patients is a rapidly advancing field with the potential to address key limitations of conventional therapy. Current evidence supports its safety and feasibility, with moderate improvements in motor outcomes. However, clinical efficacy remains heterogeneous, and its translation to functional independence is still limited. Integration with neuromodulatory techniques and further high-quality clinical trials are essential to establish its role in standard care. While not yet a substitute for conventional therapy, robotic rehabilitation represents a valuable adjunct that may significantly contribute to improving quality of life and independence for individuals living with SCI.



**FIGURE 2.** Future directions of robotic rehabilitation. Future robotic exoskeleton development will be driven by artificial intelligence, machine learning, hybrid neuromodulation strategies, and integration with virtual/augmented reality, wearable sensors, and cloud-based systems to enhance engagement, remote monitoring, and therapy optimization. To enable widespread clinical adoption, future studies must emphasize patient-centered outcomes, validate efficacy and safety through large multicenter trials, and ensure cost-effectiveness, ultimately advancing toward precision medicine with individualized rehabilitation. FES: functional electrical stimulation, tSCS: transcutaneous spinal cord stimulation, BCI: brain–computer interface.

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