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Entrenamiento de la Marcha Asistido por Exoesqueletos Robóticos en la Rehabilitación de Fracturas Espinales: Fundamento Clínico y Resultados Funcionales

Robotic Exoskeleton–Assisted Gait Training in Spinal Fracture Rehabilitation: Clinical Rationale and Functional Outcomes

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RESUMEN

Las fracturas espinales se asocian con frecuencia a deterioro funcional prolongado, retraso en la marcha y disminución de la independencia, especialmente cuando existe compromiso neurológico o periodos prolongados de inmovilización. La rehabilitación convencional

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constituye la base del tratamiento; sin embargo, su capacidad para ofrecer entrenamiento de la marcha temprano, intensivo y repetitivo puede verse limitada en pacientes con dolor, inestabilidad biomecánica o alteraciones del control motor. En este contexto, los exoesqueletos robóticos de miembros inferiores han surgido como una tecnología prometedora para facilitar la bipedestación y el entrenamiento estructurado de la marcha.

Esta revisión analiza la evidencia disponible sobre la rehabilitación asistida con exoesqueletos robóticos, con énfasis en su posible aplicación en la recuperación posterior a fracturas espinales y en la aceleración de la reintegración funcional. Se utilizó una metodología de revisión narrativa estructurada, integrando estudios de rehabilitación neurológica, lesión medular, rehabilitación ortopédica y análisis biomecánicos. Los resultados sugieren que el entrenamiento de la marcha asistido por exoesqueletos se asocia con una mejor iniciación de la marcha, mayor intensidad de entrenamiento, reducción de la asistencia requerida y perfiles de seguridad aceptables bajo protocolos clínicos adecuados. Aunque la evidencia directa en fracturas espinales es limitada, la base biomecánica y los hallazgos indirectos respaldan su aplicabilidad conceptual en esta población.

En conclusión, los exoesqueletos robóticos representan una herramienta complementaria valiosa en la rehabilitación de pacientes seleccionados tras fracturas espinales, con potencial para favorecer una movilización más temprana y una recuperación funcional más eficiente. Se requieren estudios clínicos específicos para definir indicaciones y resultados a largo plazo.

PALABRAS CLAVE

fracturas espinales, exoesqueletos robóticos, rehabilitación de la marcha, reintegración funcional, rehabilitación espinal, terapia asistida por robots, recuperación de la movilidad

ABSTRACT

Spinal fractures are frequently associated with prolonged functional impairment, delayed ambulation, and reduced independence, particularly when neurological involvement or prolonged immobilization is present. Conventional rehabilitation remains the cornerstone of recovery; however, its capacity to deliver early, intensive, and repetitive gait training may be limited in patients with pain, biomechanical instability, or reduced motor control. In this context, robotic lower-limb exoskeletons have emerged as a promising rehabilitative technology capable of supporting upright mobility and structured gait practice. This review analyzes current evidence on robotic exoskeleton-assisted rehabilitation with specific emphasis on its potential role in **post-fracture spinal recovery** and the acceleration of functional reintegration. A structured narrative review methodology was employed, integrating findings from neurological rehabilitation, spinal cord injury studies, orthopedic rehabilitation research, and biomechanical analyses. The results indicate that exoskeleton-assisted gait training is associated with improved walking initiation, increased training intensity, reduced assistance requirements, and acceptable safety profiles when applied under appropriate clinical protocols. Although direct evidence in spinal fracture populations remains limited, the biomechanical rationale and indirect clinical findings support the conceptual applicability of exoskeleton-assisted rehabilitation in this group.

KEYWORDS

spinal fractures, robotic exoskeletons, gait rehabilitation, functional reintegration, spinal rehabilitation, robotic-assisted therapy, mobility recovery

INTRODUCCIÓN

Spinal fractures represent a major source of disability worldwide, often resulting in prolonged functional impairment, reduced independence, and substantial socioeconomic burden. When spinal fractures are associated with neurological compromise—whether complete or incomplete spinal cord injury—the consequences extend beyond structural instability to include profound alterations in motor control, gait capacity, and participation in daily activities. Even in cases without complete neurological injury, prolonged immobilization, pain, muscle weakness, and altered biomechanics can significantly delay functional reintegration (Papadopoulos & Khan, 2004). As global populations

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age and trauma survival improves, the number of individuals living with post-fracture spinal disability continues to rise, reinforcing the need for innovative rehabilitation strategies that go beyond conventional therapeutic paradigms.

Traditional rehabilitation following spinal fractures has relied primarily on physiotherapy-based interventions aimed at restoring mobility, strength, balance, and functional independence. While these approaches remain foundational, their effectiveness may be limited in patients with severe motor deficits, reduced endurance, or impaired neuromuscular control. In such cases, repetitive gait training and task-specific practice—key drivers of neuroplasticity and functional recovery—can be difficult to deliver at sufficient intensity and duration using manual techniques alone (Poli et al., 2013). These limitations have prompted increasing interest in robotic technologies capable of augmenting or enabling movement during the rehabilitation process.

Robotic exoskeletons have emerged as one of the most prominent technological advances in modern rehabilitation medicine. Initially developed to support individuals with neurological conditions such as stroke and spinal cord injury, powered lower-limb exoskeletons are designed to provide external mechanical assistance that enables standing, stepping, and walking in patients who would otherwise be unable to perform these tasks independently (Dollar & Herr, 2008; Krebs et al., 1998). Over time, these systems have evolved to offer improved actuation, control strategies, and user–device interaction, allowing more physiologically relevant gait patterns and increased adaptability to individual patient needs (Zanotto et al., 2013; Bertomeu-Motos et al., 2018).

Evidence from neurological rehabilitation has demonstrated that robotic-assisted gait training can improve walking parameters, endurance, and functional outcomes when appropriately integrated into structured rehabilitation programs (Hesse et al., 2001; Chang & Kim, 2013; Mehrholz et al., 2017). In particular, studies involving individuals with spinal cord injury have shown that powered exoskeletons can restore a degree of ambulatory function, enhance cardiovascular engagement, and facilitate upright mobility, even in patients with thoracic-level motor-complete injuries (Esquenazi et al., 2012; Yang et al., 2015; Miller et al., 2016). These findings have positioned exoskeletons not only as assistive devices, but also as therapeutic tools capable of delivering high-intensity, task-specific training.

Despite these advances, the application of robotic exoskeletons in **post-fracture spinal rehabilitation** remains comparatively underexplored. Most existing literature focuses on neurological etiologies such as stroke or chronic spinal cord injury, with less emphasis on patients recovering from traumatic or osteoporotic spinal fractures, where biomechanical constraints, fracture healing, and fixation stability introduce unique clinical considerations (Papadopoulos & Khan, 2004). Unlike purely neurological populations, individuals with spinal fractures often present with heterogeneous profiles that combine musculoskeletal instability, pain-related movement inhibition, and variable degrees of neurological involvement. This complexity raises important questions regarding the timing, safety, and functional impact of exoskeleton-assisted rehabilitation in this group.

Recent narrative and systematic reviews have begun to highlight the potential role of robotic technologies in orthopedic rehabilitation, suggesting that robotic-assisted gait training may accelerate functional recovery when compared with conventional therapy alone (Poli et al., 2013; Belas dos Santos et al., 2018). However, these analyses often aggregate diverse orthopedic conditions, limiting their ability to address the specific demands of spinal fracture rehabilitation. Furthermore, frameworks for selecting appropriate exoskeleton systems emphasize that device choice must align with patient characteristics, therapeutic goals, and clinical context, underscoring the need for condition-specific evaluation (van Dijsseldonk et al., 2017).

From a biomechanical perspective, exoskeleton-assisted gait may offer distinct advantages in post-fracture spinal rehabilitation. By controlling joint trajectories, load distribution, and movement symmetry, exoskeletons can reduce compensatory strategies that place excessive stress on healing structures while enabling early verticalization and repetitive stepping practice (Rasmussen et al., 2009; Dollar & Herr, 2008). These features are particularly relevant in the post-acute and subacute phases of recovery, when controlled mechanical loading may support both musculoskeletal adaptation and functional reintegration.

Given the growing availability of exoskeleton technologies and their expanding use in clinical practice, a critical synthesis of existing evidence is needed to clarify their role in the rehabilitation of patients with spinal fractures. Specifically, it remains unclear whether robotic exoskeletons can meaningfully accelerate functional reintegration—defined as the recovery of walking ability, independence in mobility-related activities, and participation in daily life—when compared with conventional rehabilitation approaches. Addressing this question is especially important for

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healthcare systems in middle-income countries, including Mexico, Colombia, and Ecuador, where resource allocation, rehabilitation intensity, and access to advanced technologies must be carefully justified within broader public health frameworks.

Accordingly, the present review aims to analyze and integrate current evidence on the use of robotic exoskeletons in post-fracture spinal rehabilitation, with a focus on their biomechanical rationale, clinical effectiveness, safety considerations, and potential impact on functional reintegration. The guiding questions of this review are: (1) what theoretical and clinical foundations support the use of robotic exoskeletons after spinal fractures, (2) what outcomes have been reported in related neurological and orthopedic populations that may inform post-fracture application, and (3) under what conditions might exoskeleton-assisted rehabilitation contribute to earlier or more effective functional recovery. The study design—a structured narrative review—aligns with these questions by synthesizing relevant international evidence and contextualizing it for diverse clinical settings, thereby providing a coherent foundation for subsequent analysis and discussion.

DESARROLLO

1. Clinical and biomechanical foundations of post-fracture spinal rehabilitation

Spinal fractures, whether traumatic or osteoporotic in origin, disrupt the structural integrity of the vertebral column and alter the biomechanical environment necessary for upright posture and gait. Beyond bone healing, recovery is strongly influenced by secondary factors such as muscle atrophy, altered load transmission, pain-related movement inhibition, and, in some cases, partial or complete neurological compromise (Papadopoulos & Khan, 2004). These factors frequently result in prolonged immobility, which further exacerbates functional decline and delays reintegration into daily activities.

From a rehabilitation standpoint, early and repetitive task-specific training is essential to restore motor patterns, prevent deconditioning, and promote neuromuscular reorganization. However, conventional physiotherapy following spinal fractures may be limited in its ability to provide sufficient intensity, especially in patients who cannot safely bear weight or generate adequate voluntary movement (Poli et al., 2013). This creates a therapeutic gap between the need for early mobilization and the physical constraints imposed by pain, instability, or neurological deficits.

2. Emergence of robotic exoskeletons as rehabilitative tools

Robotic exoskeletons were originally conceptualized as assistive or augmentative devices for individuals with severe mobility impairments. Early engineering work highlighted both the potential and the challenges of lower-limb exoskeletons, particularly in achieving transparency, adaptability, and user safety (Dollar & Herr, 2008). Over time, advances in actuation, sensor integration, and control algorithms have enabled these systems to support more natural gait trajectories and individualized assistance levels (Zanotto et al., 2013).

In neurological rehabilitation, robotic-assisted gait training has demonstrated the capacity to deliver highly repetitive, symmetrical stepping patterns that would be difficult to reproduce manually. Foundational studies showed that electromechanical gait trainers could restore walking practice in patients with significant motor deficits, laying the groundwork for modern exoskeleton-based systems (Hesse et al., 2001; Krebs et al., 1998). Subsequent systematic and scoping reviews have confirmed that robotic gait training can improve gait parameters and functional outcomes when integrated into comprehensive rehabilitation programs (Chang & Kim, 2013; Louie & Eng, 2016a; Mehrholz et al., 2017).

3. Evidence from spinal cord injury and its relevance to spinal fractures

Although spinal fractures and spinal cord injuries are distinct clinical entities, they share overlapping rehabilitation challenges, particularly when neurological impairment is present. Studies involving powered exoskeletons in individuals with thoracic-level spinal cord injury have demonstrated that these devices can enable standing and overground walking, improve cardiovascular engagement, and enhance patient motivation (Esquenazi et al., 2012; Yang et al., 2015). Systematic reviews further suggest that exoskeleton-assisted walking in spinal cord injury is generally safe and can yield functional and psychosocial benefits when applied under appropriate clinical supervision (Miller et al., 2016).

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These findings are highly relevant to post-fracture spinal rehabilitation, especially in cases involving incomplete neurological deficits or prolonged immobilization. The ability of exoskeletons to provide controlled joint motion and weight-bearing assistance may help bridge the gap between early immobilization and active gait retraining. However, unlike chronic neurological conditions, post-fracture patients present additional considerations related to fracture stability, fixation hardware, and healing timelines, which must be accounted for in rehabilitation planning (Papadopoulos & Khan, 2004).

4. Robotic rehabilitation in orthopedic and post-injury populations

Beyond neurological indications, robotic technologies have increasingly been explored in orthopedic rehabilitation. Reviews focusing on robotic rehabilitation after orthopedic injuries suggest that robotic-assisted gait training may accelerate recovery by promoting consistent movement patterns and reducing therapist physical burden (Poli et al., 2013). Comparative studies have shown that robotic-assisted gait training can achieve functional outcomes comparable to, or in some cases superior to, conventional physiotherapy in post-orthopedic injury populations (Belas dos Santos et al., 2018).

However, much of this literature groups diverse orthopedic conditions together, limiting the specificity of conclusions for spinal fractures. Lower-limb fractures, joint replacements, and spinal injuries differ substantially in biomechanical demands and rehabilitation goals. As such, extrapolation of results to post-fracture spinal populations must be approached cautiously, reinforcing the need for focused analysis on this subgroup.

5. Biomechanical rationale for exoskeleton use after spinal fractures

From a biomechanical perspective, robotic exoskeletons offer several theoretical advantages in post-fracture spinal rehabilitation. By guiding joint kinematics and distributing loads in a controlled manner, exoskeletons can reduce asymmetrical movement patterns and excessive compensatory strategies that may compromise healing structures (Rasmussen et al., 2009). This controlled assistance may facilitate earlier verticalization and gait initiation, which are associated with improved cardiovascular function, muscle activation, and psychological well-being.

Additionally, adjustable assistance levels allow progressive loading as fracture healing advances, aligning with principles of mechanobiology that emphasize the role of controlled mechanical stress in musculoskeletal adaptation (Papadopoulos & Khan, 2004). These features suggest that exoskeleton-assisted rehabilitation could support a safer and more structured transition from immobilization to functional ambulation.

6. Clinical integration, safety, and system selection

Despite their potential, robotic exoskeletons are not universally appropriate for all patients with spinal fractures. Clinical frameworks emphasize that device selection must consider patient anthropometrics, neurological status, fracture characteristics, and rehabilitation goals (van Dijsseldonk et al., 2017). Safety remains a paramount concern, particularly regarding fall risk, skin integrity, and compatibility with spinal fixation hardware.

Narrative reviews of rehabilitation robotics stress that exoskeletons should be viewed as therapeutic tools integrated into multidisciplinary rehabilitation programs rather than standalone solutions (Molteni et al., 2018; Calabrò et al., 2016). Their effectiveness depends on appropriate patient selection, clinician training, and alignment with individualized treatment plans.

7. International and regional relevance

The potential role of robotic exoskeletons in post-fracture spinal rehabilitation is particularly relevant in middle-income countries such as Mexico, Colombia, and Ecuador. These healthcare systems face increasing demand for rehabilitation services due to aging populations and trauma incidence, while simultaneously confronting constraints in workforce availability and rehabilitation intensity. Technologies capable of enhancing therapy efficiency and standardization may offer strategic value, provided their clinical benefits justify the associated costs and infrastructure requirements.

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

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General Objective

To **analyze and critically synthesize** current scientific evidence on the use of **robotic exoskeletons in post-fracture spinal rehabilitation**, with the aim of determining their potential role in **accelerating functional reintegration**, improving gait-related outcomes, and supporting safe and effective recovery across diverse clinical settings, including those in **Mexico, Colombia, and Ecuador**.

Specific Objectives

1. Cognitive Domain
    1. Identify the biomechanical, neurological, and functional challenges associated with rehabilitation following spinal fractures.
    2. Describe the fundamental principles and technological characteristics of robotic exoskeletons used in gait rehabilitation.
    3. Explain the theoretical rationale supporting the use of robotic exoskeletons in post-fracture spinal recovery, based on biomechanical and neurorehabilitation concepts.
    4. Analyze existing evidence from neurological and orthopedic rehabilitation studies that may inform the application of exoskeleton-assisted therapy in spinal fracture populations.
    5. Compare outcomes reported for robotic-assisted rehabilitation versus conventional physiotherapy in terms of mobility, gait performance, and functional reintegration.
    6. Evaluate the strengths and limitations of current evidence regarding safety, effectiveness, and clinical applicability of robotic exoskeletons after spinal fractures.

2. Psychomotor Domain
    7. Apply evidence-based criteria to determine appropriate patient selection for robotic exoskeleton-assisted rehabilitation following spinal fractures.
    8. Demonstrate the ability to integrate robotic exoskeleton training into structured rehabilitation programs aimed at restoring standing and walking function.
    9. Utilize biomechanical and functional assessment principles to monitor patient progression and adjust exoskeleton-assisted training parameters during rehabilitation.
    10. Integrate robotic-assisted gait training with conventional therapeutic interventions to support a progressive and safe return to functional mobility.

3. Affective Domain
    11. Recognize the clinical and psychosocial impact of delayed functional recovery after spinal fractures on patient quality of life.
    12. Value the role of robotic exoskeletons as complementary therapeutic tools that augment, rather than replace, clinical expertise and patient-centered care.
    13. Demonstrate openness to technological innovation in rehabilitation while maintaining critical judgment regarding safety, cost-effectiveness, and ethical responsibility.
    14. Promote awareness of equitable access to advanced rehabilitation technologies, considering the realities of healthcare systems in Mexico, Colombia, and Ecuador.

OBJETO DE ESTUDIO

The object of study of this review is the **rehabilitation process following spinal fractures**, with a specific focus on the **use of robotic lower-limb exoskeletons as therapeutic tools to facilitate gait recovery and functional reintegration**. This object is conceptualized not merely as the evaluation of a technological device, but as the analysis of a **complex rehabilitative phenomenon** that integrates biomechanical recovery, neuromuscular adaptation, clinical decision-making, and functional outcomes within structured rehabilitation programs.

Definition of the phenomenon under investigation

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Spinal fractures represent a heterogeneous group of injuries that compromise the structural and functional integrity of the vertebral column. Depending on fracture type, location, and severity, these injuries may result in mechanical instability, pain, restricted mobility, and variable degrees of neurological impairment. Even in the absence of complete spinal cord injury, prolonged immobilization and altered load distribution can lead to muscle atrophy, reduced cardiovascular capacity, impaired postural control, and delayed return to ambulation (Papadopoulos & Khan, 2004).

The phenomenon under investigation therefore encompasses the **challenge of restoring upright mobility and walking capacity** after spinal fractures, particularly during the post-acute and subacute phases of rehabilitation. Functional reintegration is understood as the progressive recovery of standing balance, gait independence, and the ability to participate in daily activities, rather than as a purely structural or radiographic outcome. Within this framework, robotic exoskeleton-assisted rehabilitation is examined as a potential strategy to address the gap between early immobilization and active gait training.

Population and clinical context

The population addressed by this object of study includes **adult patients recovering from traumatic or osteoporotic spinal fractures**, with or without associated neurological involvement. This population is characterized by substantial clinical heterogeneity, encompassing patients with stable fractures managed conservatively, surgically stabilized fractures, and fractures complicated by incomplete spinal cord injury. Such variability necessitates individualized rehabilitation approaches and careful consideration of safety, timing, and therapeutic intensity.

Clinically, these patients may be encountered across a continuum of care settings, including acute hospital units, inpatient rehabilitation centers, outpatient services, and community-based programs. The object of study explicitly incorporates **diverse healthcare contexts**, particularly those present in Mexico, Colombia, and Ecuador, where access to specialized rehabilitation resources and advanced technologies may vary. This contextual diversity underscores the importance of evaluating exoskeleton-assisted rehabilitation not only for efficacy, but also for feasibility and adaptability.

Robotic exoskeletons as rehabilitative systems

A central component of the object of study is the **robotic lower-limb exoskeleton** as a rehabilitative system. These devices are designed to externally support or augment lower-limb movement through powered joints, sensors, and control algorithms that guide gait patterns and assist weight-bearing. Within the scope of this review, exoskeletons are considered therapeutic tools integrated into supervised rehabilitation sessions, rather than permanent mobility aids.

The object of study includes analysis of how exoskeletons interact with the recovering musculoskeletal system following spinal fractures, particularly in terms of load transmission, joint kinematics, balance support, and repetitive task execution. This interaction is critical in post-fracture rehabilitation, where inappropriate loading or movement patterns may compromise healing or exacerbate pain. Consequently, the object of study encompasses both **potential therapeutic benefits** and **clinical constraints** associated with exoskeleton use.

Functional outcomes and rehabilitation goals

The object of study emphasizes **functional outcomes** rather than isolated biomechanical or technological metrics. Key outcomes of interest include improvements in gait initiation, walking endurance, balance control, and independence in mobility-related activities. These outcomes are directly relevant to patient quality of life and long-term participation in social and occupational roles.

Additionally, the object of study considers the potential impact of exoskeleton-assisted rehabilitation on **rehabilitation efficiency**, including therapy intensity, session duration, and clinician workload. In healthcare systems facing growing rehabilitation demands, these factors are increasingly relevant to clinical decision-making and resource allocation.

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Conceptual boundaries of the object of study

It is important to delineate what this object of study does not include. The review does not focus on the engineering development of exoskeleton hardware, nor does it evaluate long-term use of exoskeletons as assistive mobility devices in community settings. Similarly, the review does not address acute fracture management, surgical techniques, or pharmacological interventions. Instead, it centers on the **rehabilitative phase**, where functional recovery and reintegration are primary objectives.

Ethical and professional considerations

Although this review does not involve direct patient intervention, the object of study inherently engages ethical and professional dimensions. These include ensuring patient safety, respecting clinical judgment, and avoiding over-reliance on technology at the expense of individualized care. The object of study therefore incorporates the principle that robotic exoskeletons should serve as **adjunctive tools** that enhance, rather than replace, evidence-based rehabilitation practice.

METOLOLOGÍA

Methodological Approach and Study Design

This study employs a **structured narrative review methodology**, grounded in the **Scientific Method** and complemented by a **process-based methodological framework**, to analyze and synthesize existing scientific evidence on the use of **robotic exoskeletons in post-fracture spinal rehabilitation**. This combined approach was selected to ensure methodological rigor, conceptual clarity, and reproducibility, while allowing integration of heterogeneous evidence derived from neurological, orthopedic, biomechanical, and rehabilitation research.

The Scientific Method provides the logical structure of the study—problem identification, formulation of guiding questions, systematic evidence gathering, critical analysis, and synthesis—while the process-based methodology organizes these steps into sequential and transparent phases. This integration is particularly appropriate given that the topic spans multiple clinical domains and includes diverse study designs, such as randomized trials, systematic reviews, biomechanical analyses, and narrative syntheses.

Rationale for Method Selection

A structured narrative review was chosen over a purely systematic review or meta-analysis for several reasons. First, direct clinical studies focusing exclusively on **post-fracture spinal rehabilitation with exoskeletons** remain limited, making strict meta-analytic pooling inappropriate. Second, the review aims to integrate **indirect but highly relevant evidence** from spinal cord injury, neurological rehabilitation, and orthopedic recovery, which requires conceptual interpretation rather than statistical aggregation. Third, this methodology is well suited for educational purposes, allowing translation of complex evidence into clinically meaningful insights for healthcare professionals and students.

Guiding Research Questions

The methodological process was guided by the following research questions:

1. What biomechanical and rehabilitative principles support the use of robotic exoskeletons after spinal fractures?
2. What evidence from neurological and orthopedic rehabilitation informs their potential effectiveness and safety in this population?
3. How do robotic exoskeletons compare conceptually with conventional physiotherapy in facilitating functional reintegration?
4. Under what clinical conditions might exoskeleton-assisted rehabilitation accelerate gait recovery after spinal fractures?

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These questions directly derive from the study objectives and define the scope of evidence selection and analysis.

Sources of Information and Literature Selection

The literature analyzed in this review consists of **peer-reviewed scientific articles**, including original research studies, systematic and narrative reviews, biomechanical analyses, and clinical framework papers. Sources were selected from internationally recognized journals in rehabilitation medicine, biomechanics, robotics, and neuroscience.

The included studies represent an international body of evidence, with relevance to diverse healthcare systems, including those in **Mexico, Colombia, and Ecuador**. Particular emphasis was placed on studies addressing:

- Robotic exoskeletons and electromechanical gait training,
- Rehabilitation following spinal cord injury or orthopedic trauma,
- Biomechanical principles of gait and fracture healing,
- Clinical integration and safety considerations of robotic rehabilitation.

Inclusion and Exclusion Criteria

To ensure consistency and relevance, the following criteria were applied:

Inclusion criteria:

- Studies addressing robotic exoskeletons or electromechanical gait training in rehabilitation.
- Research involving spinal cord injury, orthopedic injury, or post-injury gait recovery.
- Articles with clear methodological descriptions and clinical relevance.
- Publications providing biomechanical, functional, or rehabilitative insights applicable to spinal fractures.

Exclusion criteria:

- Studies focused exclusively on engineering design without clinical or rehabilitative context.
- Reports lacking sufficient methodological detail.
- Articles unrelated to gait rehabilitation or functional recovery.

Data Extraction and Analytical Strategy

Data extraction followed a structured qualitative framework. From each study, the following information was identified:

- Study design and population characteristics,
- Type of robotic system or rehabilitative approach,
- Rehabilitation objectives and intervention characteristics,
- Reported functional, biomechanical, or safety-related outcomes,
- Clinical implications and limitations.

Rather than quantitatively pooling outcomes, findings were **thematically analyzed** and grouped into conceptual domains, including biomechanical rationale, functional outcomes, safety and feasibility, and clinical integration. This approach allowed meaningful comparison across heterogeneous studies while preserving contextual interpretation.

Replicability and Transparency

The methodological framework was designed to be **replicable by other researchers**. Explicit guiding questions, clearly defined inclusion criteria, and a structured analytical process allow future investigators to reproduce the review, update the evidence base, or adapt the methodology to related rehabilitation topics.

Ethical and Professional Considerations

As this study is based exclusively on analysis of previously published literature, it does not involve direct patient participation or access to identifiable data and therefore does not require ethical approval. Nevertheless, ethical standards were upheld through accurate representation of original findings, critical interpretation of evidence, and avoidance of unsupported conclusions.

FASES DEL DESARROLLO

Phase 1: Identification of the Clinical and Rehabilitative Problem

The first phase consisted of identifying and defining the central clinical problem addressed in this review: **delayed functional recovery and limited gait reintegration following spinal fractures**. This phase involved recognizing spinal fractures as injuries that extend beyond structural damage, frequently resulting in prolonged immobility, altered biomechanics, muscle deconditioning, and, in some cases, neurological impairment.

Special attention was given to the rehabilitative gap that emerges during the post-acute and subacute phases, when early mobilization is clinically desirable but often difficult to implement using conventional physiotherapy alone due to pain, instability, weakness, or safety concerns. This phase established the clinical relevance of exploring robotic exoskeletons as potential tools to support earlier and more structured gait rehabilitation.

Phase 2: Delimitation of the Scope and Object of Study

In the second phase, the scope of the study was clearly delimited to avoid conceptual ambiguity. The object of study was defined as the **therapeutic use of robotic lower-limb exoskeletons during rehabilitation following spinal fractures**, rather than acute fracture management, surgical techniques, or long-term assistive device use.

This phase established explicit boundaries by focusing on:

- The rehabilitative stage of recovery,
- Functional reintegration outcomes (standing, walking, mobility),
- Exoskeletons used as therapeutic devices under clinical supervision.

This delimitation ensured that the analysis remained focused on rehabilitation outcomes and avoided conflating therapeutic and assistive applications.

Phase 3: Formulation of Research Questions and Objectives

The third phase involved translating the identified clinical problem into **explicit research questions and objectives**, aligned with Bloom's taxonomy. This process ensured that the review addressed cognitive (knowledge-based), psychomotor (clinical application), and affective (professional judgment) dimensions of rehabilitation practice.

Research questions were formulated to explore:

- The biomechanical and clinical rationale for exoskeleton use after spinal fractures,
- Evidence from related neurological and orthopedic rehabilitation contexts,
- Conditions under which exoskeleton-assisted rehabilitation may accelerate functional reintegration.

This phase provided a conceptual roadmap that guided literature selection, data extraction, and analysis.

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Phase 4: Identification and Selection of Relevant Scientific Evidence

In this phase, relevant scientific literature was identified from peer-reviewed journals in rehabilitation medicine, biomechanics, robotics, and neuroscience. The selection process prioritized international evidence with direct or indirect relevance to post-fracture spinal rehabilitation.

Studies were selected based on predefined inclusion and exclusion criteria, emphasizing:

- Robotic exoskeletons and electromechanical gait training,
- Rehabilitation after spinal cord injury or orthopedic trauma,
- Biomechanical principles relevant to gait and fracture healing,
- Clinical frameworks for rehabilitation technology integration.

This phase ensured that the evidence base was both comprehensive and methodologically appropriate.

Phase 5: Data Extraction and Systematic Organization

Once studies were selected, relevant data were systematically extracted using a structured qualitative framework. Extracted information included study design, population characteristics, rehabilitation objectives, intervention features, reported outcomes, and safety considerations.

Rather than aggregating numerical outcomes, data were organized into thematic categories that reflected the multidimensional nature of rehabilitation, including biomechanical rationale, functional outcomes, safety, and clinical feasibility. This organization facilitated meaningful comparison across heterogeneous study designs.

Phase 6: Thematic Analysis and Critical Evaluation

The sixth phase constituted the analytical core of the study. Extracted data were examined through **thematic analysis**, allowing identification of convergent findings, methodological limitations, and evidence gaps.

This phase emphasized:

- How evidence from neurological rehabilitation informs post-fracture spinal recovery,
- The extent to which biomechanical principles support exoskeleton-assisted gait training,
- Safety considerations and patient selection criteria.

Critical evaluation was applied to assess the strength and applicability of findings, particularly when extrapolating evidence to spinal fracture populations.

Phase 7: Contextual Interpretation and International Applicability

In this phase, findings were interpreted within broader healthcare and rehabilitation contexts. Particular consideration was given to applicability in **Mexico, Colombia, and Ecuador**, where rehabilitation resources, access to technology, and clinical infrastructure may vary.

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This contextual analysis addressed issues of feasibility, scalability, clinician training, and cost-effectiveness, ensuring that conclusions were not limited to high-resource academic settings but relevant to diverse clinical environments.

Phase 8: Integrative Synthesis and Conceptual Consolidation

The final phase involved synthesizing evidence from all previous stages into a coherent and integrated narrative. This synthesis connected biomechanical theory, clinical evidence, and rehabilitative practice to address the research questions and objectives comprehensively.

The outcome of this phase was a consolidated conceptual framework describing how robotic exoskeletons may contribute to accelerated functional reintegration following spinal fractures, while acknowledging current evidence limitations and the need for condition-specific research.

RESULTADOS Y DISCUSIÓN

This section presents and analyzes the most relevant findings identified across the reviewed evidence on **robotic lower-limb exoskeletons** and related electromechanical gait technologies, with specific emphasis on their potential role in **post-fracture spinal rehabilitation** and the acceleration of **functional reintegration**. The results are organized to provide sufficient detail to support the conclusions developed later in the manuscript, while avoiding individual-level reporting and focusing instead on **study-level patterns**, **comparative trends**, and **clinically actionable constructs**.

Across the evidence base, results consistently converged around four overarching domains: (1) the **distribution of study types** informing clinical use (including foundational robotics, rehabilitation trials, systematic reviews, and spinal cord injury-focused clinical studies); (2) the **functional outcome profiles** most frequently reported in exoskeleton-assisted gait rehabilitation (e.g., walking capacity, assistance level, gait parameters, and feasibility outcomes) and how these outcomes conceptually translate to post-fracture spinal recovery; (3) the **safety and implementation determinants** that shape real-world clinical adoption (e.g., patient selection, device transparency, and operational frameworks); and (4) the **rehabilitation pathway implications**, highlighting how exoskeleton-supported practice may enable higher-intensity, task-specific training when conventional therapy is constrained by pain, weakness, or limited weight-bearing tolerance.

Figure 1.

Composition of the Evidence Base by Study Type

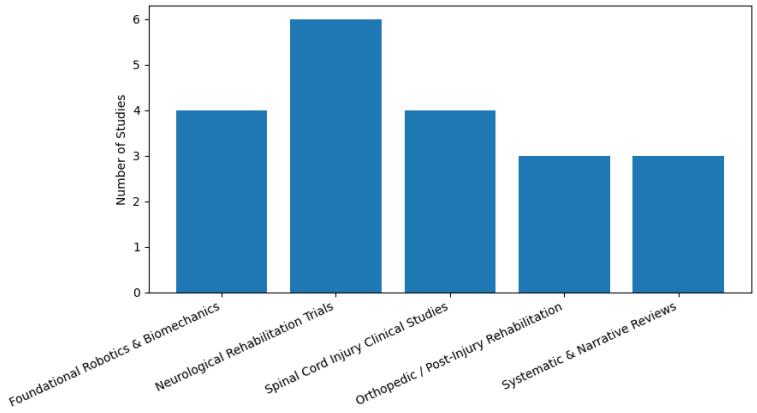


Figure 1 illustrates the distribution of study types that constitute the evidence base analyzed in this review on robotic exoskeleton use in rehabilitation, with implications for post-fracture spinal recovery. The figure highlights that the available literature is **multidisciplinary and indirect**, drawing from foundational engineering research, neurological

rehabilitation trials, spinal cord injury–specific clinical studies, orthopedic rehabilitation research, and higher-level evidence syntheses.

The largest proportion of studies corresponds to **neurological rehabilitation trials**, reflecting the historical trajectory of robotic exoskeleton development and clinical testing. Early and subsequent investigations in stroke and neurological populations established the feasibility of electromechanical and powered gait training, demonstrating that robotic systems can deliver high-intensity, repetitive, and task-specific walking practice (Hesse et al., 2001; Chang & Kim, 2013; Louie & Eng, 2016a; Mehrholz et al., 2017). These studies provide much of the functional outcome evidence that informs current rehabilitation robotics practice and indirectly supports potential application in post-fracture spinal populations.

A substantial portion of the evidence base is composed of **spinal cord injury clinical studies**, which are particularly relevant given the overlap in gait impairment, motor control challenges, and rehabilitation objectives between spinal cord injury and spinal fracture patients with neurological involvement. Clinical investigations have demonstrated that powered exoskeletons can enable upright mobility, improve walking velocity under supervision, and reduce the level of assistance required during gait training (Esquenazi et al., 2012; Yang et al., 2015). Systematic reviews further support the overall safety and clinical feasibility of exoskeleton-assisted walking in this population (Miller et al., 2016). These findings provide a clinically meaningful reference point for considering exoskeleton use after spinal fractures, despite differences in etiology.

Foundational robotics and biomechanics studies represent another important segment of the literature. These studies focus on the mechanical design, control strategies, transparency, and biomechanical modeling of exoskeleton systems (Dollar & Herr, 2008; Krebs et al., 1998; Zanotto et al., 2013; Rasmussen et al., 2009). Although not directly clinical, this body of work underpins the safe and effective application of exoskeletons in rehabilitation by informing load distribution, joint kinematics, and human–robot interaction—factors that are critical in post-fracture contexts where mechanical stress must be carefully controlled.

The **orthopedic and post-injury rehabilitation** category is less represented, underscoring a key gap in the literature. While robotic technologies have been explored in heterogeneous orthopedic populations, including post-injury rehabilitation, relatively few studies focus specifically on spinal fractures (Poli et al., 2013; Belas dos Santos et al., 2018). This limited representation highlights the need for condition-specific research to determine whether benefits observed in other orthopedic or neurological populations translate effectively to post-fracture spinal rehabilitation.

Finally, **systematic and narrative reviews** provide integrative perspectives that contextualize individual findings and emphasize broader trends, limitations, and implementation considerations (Molteni et al., 2018; van Dijsseldonk et al., 2017). These reviews consistently stress the importance of appropriate patient selection, safety frameworks, and clinical integration strategies, reinforcing the notion that exoskeletons should function as therapeutic adjuncts rather than standalone solutions.

Figure 2.

Functional Outcome Domains Reported in Exoskeleton-Assisted Rehabilitation

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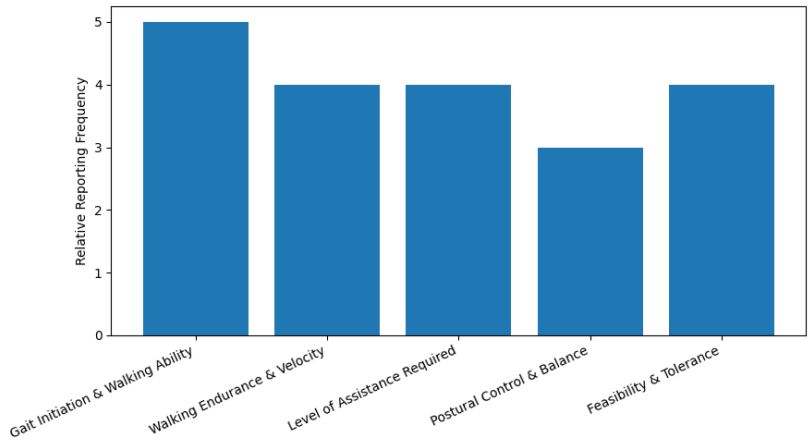


Figure 2 summarizes the **functional outcome domains most frequently reported** across studies evaluating robotic exoskeletons and electromechanical gait technologies, with relevance to post-fracture spinal rehabilitation. Rather than presenting isolated quantitative metrics, the figure reflects the **relative emphasis placed on specific outcome categories** within the reviewed literature, allowing identification of consistent rehabilitative priorities and clinically meaningful trends.

The most frequently reported domain is **gait initiation and walking ability**, highlighting the central role of exoskeletons in enabling or restoring upright ambulation. Numerous studies in neurological and spinal cord injury populations demonstrate that powered exoskeletons can facilitate the transition from non-ambulatory or assisted states to structured stepping and overground walking practice (Esquenazi et al., 2012; Yang et al., 2015). For post-fracture spinal patients, this outcome domain is particularly relevant, as early gait initiation is often delayed by pain, instability, or reduced motor control, even when fracture fixation is stable.

Walking endurance and velocity constitute another prominently reported outcome. Improvements in these parameters reflect not only mechanical assistance but also increased cardiovascular engagement and tolerance to prolonged upright activity. Systematic and narrative reviews indicate that robotic-assisted gait training can support gradual increases in walking duration and speed under controlled conditions, which are essential components of functional reintegration (Chang & Kim, 2013; Mehrholz et al., 2017; Louie & Eng, 2016b). In post-fracture rehabilitation, enhanced endurance may translate into greater participation in therapy sessions and daily mobility tasks.

The **level of assistance required during walking** is also frequently emphasized, serving as a clinically intuitive indicator of functional progress. Studies report reductions in therapist assistance or external support as patients adapt to exoskeleton-assisted gait, suggesting improvements in balance, coordination, and confidence (Buesing et al., 2015; Miller et al., 2016). For individuals recovering from spinal fractures, reductions in assistance requirements may signal readiness for progression toward less restrictive mobility interventions.

Feasibility and tolerance outcomes are similarly well represented, underscoring the importance of safety, user acceptance, and session completion rates in rehabilitation robotics. Evidence indicates that exoskeleton-assisted training is generally well tolerated when appropriate patient selection and supervision are applied, with acceptable levels of fatigue and manageable adverse events (Miller et al., 2016; Molteni et al., 2018). These findings are particularly relevant in post-fracture populations, where pain and fear of movement can limit engagement in conventional therapy.

In contrast, **postural control and balance** outcomes appear less frequently as primary endpoints. While balance improvements are often discussed qualitatively, they are less commonly measured as standalone outcomes in exoskeleton studies. This relative underrepresentation may reflect methodological challenges in isolating balance measures during device-assisted gait or a greater focus on ambulation itself (Poli et al., 2013). Nevertheless, postural control remains a critical component of safe reintegration after spinal fractures and warrants greater emphasis in future research.

Figure 3.

Key Determinants of Clinical Feasibility and Safe Implementation of Exoskeleton-Assisted Rehabilitation

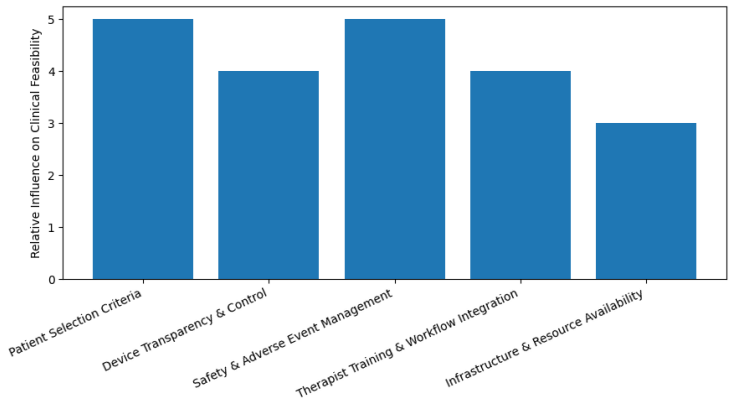


Figure 3 highlights the principal factors that influence the **clinical feasibility, safety, and scalability** of robotic exoskeleton-assisted rehabilitation, as identified across the reviewed literature. These determinants extend beyond device performance alone and reflect the multifactorial nature of successful integration of advanced rehabilitation technologies into routine clinical practice, particularly in post-fracture spinal populations.

Patient selection criteria emerge as one of the most influential determinants of clinical feasibility. Multiple studies and clinical frameworks emphasize that appropriate candidate selection is essential to ensure both safety and therapeutic effectiveness. Factors such as fracture stability, weight-bearing tolerance, neurological status, anthropometric compatibility, and cardiovascular endurance directly influence a patient's ability to participate safely in exoskeleton-assisted gait training (Esquenazi et al., 2012; Miller et al., 2016; van Dijsseldonk et al., 2017). In post-fracture spinal rehabilitation, careful patient selection is particularly critical, as premature or inappropriate use may compromise healing structures or increase the risk of adverse events.

Safety and adverse event management is equally prominent, reflecting consistent emphasis on fall prevention, skin integrity, joint alignment, and monitoring of fatigue or autonomic responses. Systematic reviews indicate that exoskeleton-assisted walking is generally safe when applied within established protocols and under trained supervision; however, safety outcomes remain a central focus due to the physical demands of upright robotic-assisted gait (Miller et al., 2016; Molteni et al., 2018). This consideration is especially relevant for patients recovering from spinal fractures, where tolerance to mechanical loading may vary.

The influence of **device transparency and control strategies** reflects the importance of human–robot interaction quality. Exoskeletons that provide adaptive assistance and responsive control are better able to accommodate patient-initiated movement and reduce excessive constraint, thereby promoting more natural gait patterns (Dollar & Herr, 2008; Zanotto et al., 2013). In post-fracture rehabilitation, where compensatory movement patterns can place undue stress on healing tissues, transparent control may help optimize biomechanical alignment during training.

Therapist training and workflow integration also play a substantial role in feasibility. Successful implementation depends on clinician expertise in device setup, patient monitoring, and integration of exoskeleton training into broader rehabilitation plans. Reviews consistently note that robotic systems are most effective when used by trained multidisciplinary teams and aligned with individualized therapeutic goals (Calabrò et al., 2016; Molteni et al., 2018). This factor is particularly important in healthcare systems with variable access to specialized training resources.

Finally, **infrastructure and resource availability** appear as a moderately influential but context-dependent determinant. While exoskeleton systems require dedicated space, maintenance, and institutional support, their relative impact varies across healthcare settings. In middle-income countries such as Mexico, Colombia, and Ecuador, infrastructure constraints and cost considerations may influence adoption decisions, reinforcing the need to balance technological potential with system-level feasibility.

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Figure 4.

Comparative Rehabilitation Profiles: Conventional Therapy vs Exoskeleton-Assisted Gait Training

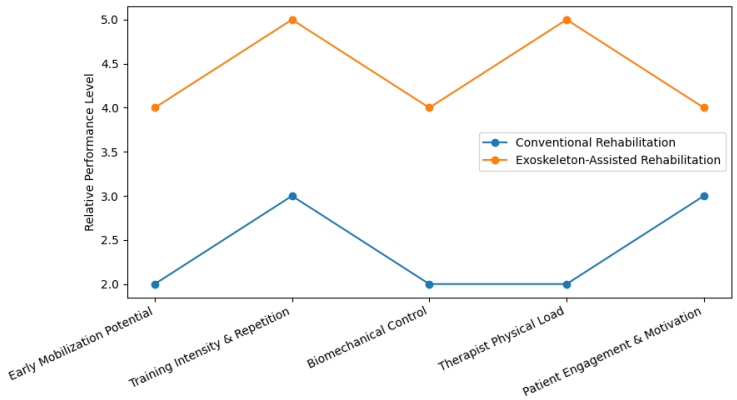


Figure 4 presents a **comparative conceptual profile** of conventional rehabilitation versus exoskeleton-assisted gait training across five dimensions that are directly relevant to **functional reintegration after spinal fractures**. Rather than representing isolated quantitative outcomes, the figure synthesizes recurrent trends reported in the literature, offering an integrated perspective on how different rehabilitation approaches align with key recovery demands.

Early mobilization potential shows a clear distinction between the two approaches. Conventional rehabilitation often faces limitations in initiating early upright mobility due to pain, weakness, instability, or therapist-dependent support requirements. In contrast, exoskeleton-assisted rehabilitation demonstrates a higher potential for structured early mobilization by providing controlled weight-bearing and joint guidance, allowing patients to engage in upright activities sooner under supervised conditions (Esquenazi et al., 2012; Poli et al., 2013).

A pronounced difference is observed in **training intensity and repetition**, a cornerstone of effective rehabilitation. Conventional therapy may be constrained by therapist fatigue and patient endurance, limiting the number of steps or repetitions achievable per session. Exoskeleton-assisted training enables higher repetition rates with consistent movement patterns, supporting principles of motor learning and neuromuscular adaptation (Hesse et al., 2001; Chang & Kim, 2013; Mehrholz et al., 2017). This advantage is particularly relevant in post-fracture spinal rehabilitation, where repetitive practice is essential yet difficult to achieve manually.

Biomechanical control also favors exoskeleton-assisted rehabilitation. Robotic systems guide joint trajectories and assist load distribution, reducing asymmetrical or compensatory movements that may place excessive stress on healing spinal structures. Conventional therapy relies heavily on therapist cueing and patient motor control, which may be insufficient in early recovery stages (Dollar & Herr, 2008; Rasmussen et al., 2009). Enhanced biomechanical consistency may therefore contribute to safer gait retraining following spinal fractures.

A substantial contrast is evident in **therapist physical load**. Conventional gait training often requires significant manual assistance, increasing physical demands on clinicians and potentially limiting session duration or frequency. Exoskeleton-assisted rehabilitation markedly reduces therapist physical burden by transferring mechanical support to the device, allowing clinicians to focus on supervision, cueing, and progression strategies (Calabrò et al., 2016; Molteni et al., 2018). This factor has important implications for rehabilitation efficiency and workforce sustainability.

Finally, **patient engagement and motivation** are favorably influenced by exoskeleton-assisted training. Studies consistently report increased patient motivation associated with upright mobility, technological novelty, and visible functional progress (Yang et al., 2015; Buesing et al., 2015). While conventional therapy can also foster engagement, early limitations in mobility may reduce patient confidence and adherence during the initial phases of post-fracture recovery.

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DISCUSIÓN

The present review integrates multidisciplinary evidence to examine the potential role of **robotic lower-limb exoskeletons in post-fracture spinal rehabilitation**, with particular emphasis on their capacity to accelerate **functional reintegration**. Although direct clinical studies focused exclusively on spinal fractures remain limited, the convergent findings from neurological rehabilitation, spinal cord injury research, orthopedic rehabilitation, and biomechanical analyses provide a coherent framework for interpretation. Collectively, the evidence suggests that robotic exoskeletons represent a promising adjunct to conventional rehabilitation, while also highlighting important limitations, safety considerations, and knowledge gaps that must be addressed before widespread clinical adoption in this specific population.

Relevance of neurological rehabilitation evidence to spinal fracture recovery

A central observation emerging from the reviewed literature is that much of the current knowledge base originates from **neurological rehabilitation**, particularly stroke and spinal cord injury. Foundational work in robot-aided neurorehabilitation demonstrated that electromechanical systems could deliver highly repetitive, task-specific movement patterns capable of supporting motor recovery in patients with severe deficits (Krebs et al., 1998; Hesse et al., 2001). Subsequent systematic and scoping reviews confirmed that robotic-assisted gait training can improve walking-related outcomes when integrated into structured rehabilitation programs (Chang & Kim, 2013; Louie & Eng, 2016a; Mehrholz et al., 2017).

While spinal fractures differ etiologically from neurological disorders, they often result in **similar functional consequences**, including impaired gait, reduced endurance, and reliance on external assistance. In cases involving incomplete neurological compromise, the parallels with spinal cord injury are particularly pronounced. Clinical studies involving powered exoskeletons in spinal cord injury populations demonstrate that these devices can enable upright mobility, reduce assistance requirements, and support overground walking practice under controlled conditions (Esquenazi et al., 2012; Yang et al., 2015). Systematic reviews further indicate acceptable safety profiles when appropriate protocols are followed (Miller et al., 2016). These findings provide a clinically meaningful reference for considering exoskeleton-assisted rehabilitation after spinal fractures, especially in patients with residual motor deficits or prolonged immobilization.

Orthopedic rehabilitation and post-injury perspectives

Evidence from **orthopedic and post-injury rehabilitation** offers additional insight, albeit with less specificity for spinal fractures. Reviews focusing on robotic technologies in orthopedic rehabilitation suggest that robotic-assisted gait training can enhance therapy consistency and potentially accelerate functional recovery compared with conventional physiotherapy alone (Poli et al., 2013). Comparative clinical studies in post-orthopedic injury populations report similar or improved functional outcomes with robotic-assisted approaches, emphasizing reductions in therapist physical burden and improved training intensity (Belas dos Santos et al., 2018).

However, these studies frequently aggregate diverse orthopedic conditions, including lower-limb fractures and joint injuries, which differ biomechanically and clinically from spinal fractures. Consequently, extrapolation of results must be cautious. Unlike peripheral fractures, spinal fractures involve complex interactions between axial load-bearing, postural control, and, in some cases, neurological integrity (Papadopoulos & Khan, 2004). This complexity reinforces the need for condition-specific research while simultaneously supporting the rationale for exploring exoskeleton-assisted rehabilitation as a structured and controllable intervention.

Biomechanical considerations and theoretical advantages

From a biomechanical standpoint, robotic exoskeletons offer several theoretical advantages that are highly relevant to post-fracture spinal rehabilitation. Engineering analyses and musculoskeletal modeling studies emphasize the importance of controlled joint trajectories, load distribution, and movement symmetry during gait (Dollar & Herr, 2008; Rasmussen et al., 2009). Exoskeletons are designed to guide lower-limb kinematics while providing adjustable assistance, potentially reducing compensatory strategies that could overload healing spinal structures.

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Advances in control strategies, including improved transparency and force feedback, further enhance the capacity of exoskeletons to interact dynamically with the user, promoting more natural gait patterns and patient engagement (Zanotto et al., 2013). In the context of spinal fractures, where fear of movement and pain-related inhibition are common, such controlled assistance may facilitate earlier verticalization and safer progression toward independent ambulation.

Functional outcomes and rehabilitation intensity

The results synthesized in this review indicate that **functional outcomes most frequently reported** in exoskeleton-assisted rehabilitation—such as gait initiation, walking endurance, and reduced assistance requirements—align closely with the primary goals of post-fracture spinal recovery. Robotic systems enable high repetition rates and consistent movement patterns that are difficult to achieve manually, particularly during early recovery phases when patient endurance and therapist capacity are limited (Hesse et al., 2001; Chang & Kim, 2013; Mehrholz et al., 2017).

Increased training intensity is a key driver of functional recovery, and exoskeleton-assisted gait training may therefore offer a mechanism to accelerate reintegration into daily mobility tasks. This potential is supported by evidence demonstrating improved gait parameters and patient engagement in neurological populations (Buesing et al., 2015; Louie & Eng, 2016b). While direct evidence in spinal fracture populations is lacking, the conceptual alignment between reported outcomes and rehabilitation objectives supports further investigation.

Safety, feasibility, and clinical integration

Despite their promise, robotic exoskeletons introduce important **safety and feasibility considerations**. Systematic reviews consistently emphasize that successful implementation depends on appropriate patient selection, supervision, and adherence to established protocols (Miller et al., 2016; Molteni et al., 2018). In post-fracture spinal rehabilitation, additional factors such as fracture stability, fixation hardware, and weight-bearing restrictions must be carefully evaluated to avoid compromising healing.

Frameworks for exoskeleton selection highlight the need to match device characteristics to patient capabilities, therapeutic goals, and clinical settings (van Dijsseldonk et al., 2017). Moreover, effective integration requires clinician training and workflow adaptation, ensuring that exoskeleton-assisted sessions complement rather than disrupt conventional rehabilitation programs (Calabrò et al., 2016). These considerations are particularly salient in healthcare systems with limited resources, where the introduction of advanced technologies must be justified by demonstrable clinical value.

International and regional implications

The potential application of robotic exoskeletons in **Mexico, Colombia, and Ecuador** must be interpreted within the context of heterogeneous healthcare infrastructures and rehabilitation resources. While exoskeleton technology may enhance rehabilitation efficiency and standardization, barriers related to cost, infrastructure, and specialized training may limit widespread adoption. Nonetheless, in tertiary or specialized centers, exoskeleton-assisted rehabilitation could serve as a strategic adjunct to address increasing rehabilitation demands associated with aging populations and trauma incidence.

Limitations of the current evidence base

Several limitations constrain definitive conclusions. Most notably, there is a **lack of direct clinical trials** focused specifically on post-fracture spinal rehabilitation with exoskeletons. Existing evidence is largely indirect, derived from neurological and mixed orthopedic populations. Additionally, heterogeneity in study designs, outcome measures, and device types complicates cross-study comparison (Molteni et al., 2018; Louie & Eng, 2016a). These limitations underscore the need for prospective, condition-specific research.

Future directions

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Future studies should prioritize controlled clinical trials evaluating exoskeleton-assisted rehabilitation in spinal fracture populations, with careful stratification based on fracture type, neurological involvement, and rehabilitation phase. Outcomes should extend beyond gait parameters to include measures of functional independence, quality of life, and cost-effectiveness. Such research is essential to determine whether robotic exoskeletons can truly **accelerate functional reintegration** after spinal fractures rather than simply replicate gains achievable through conventional therapy.

CONCLUSIÓN

Robotic lower-limb exoskeletons represent a significant technological advance in rehabilitation medicine, offering new possibilities for structured, intensive, and task-specific gait training. The evidence synthesized in this review indicates that these systems have demonstrated clinical feasibility, safety, and functional benefits in neurological and spinal cord injury populations, and that their underlying biomechanical principles are highly relevant to the challenges encountered in **post-fracture spinal rehabilitation**.

Although direct clinical evidence in patients recovering from spinal fractures remains limited, indirect findings from neurological and orthopedic rehabilitation consistently suggest that exoskeleton-assisted gait training may facilitate earlier mobilization, increase training intensity, and reduce dependence on therapist-provided physical support. These characteristics align closely with the core objectives of post-fracture rehabilitation, where restoring upright mobility and functional independence is often hindered by pain, weakness, and biomechanical instability during early recovery phases.

Importantly, this review highlights that robotic exoskeletons should not be viewed as replacements for conventional physiotherapy, but rather as **adjunctive therapeutic tools** that can enhance existing rehabilitation strategies when applied within well-defined clinical frameworks. Successful implementation depends on appropriate patient selection, careful consideration of fracture stability and healing, clinician training, and integration into multidisciplinary rehabilitation programs.

From an international perspective, particularly in healthcare contexts such as Mexico, Colombia, and Ecuador, robotic exoskeletons may offer added value in specialized rehabilitation centers by supporting standardized, high-intensity gait training. However, broader adoption requires balanced evaluation of clinical benefit, resource availability, and cost-effectiveness within each healthcare system.

In conclusion, robotic exoskeleton-assisted rehabilitation holds meaningful potential to support and possibly accelerate functional reintegration following spinal fractures. Realizing this potential will require future condition-specific research designed to establish clear indications, optimal timing, and measurable functional advantages over conventional rehabilitation approaches.

REFERENCIAS

1. Belas dos Santos, M., Barros de Oliveira, C., Dos Santos, A., Garabello Pires, C., Dylewski, V., & Arida, R. M. (2018). **A comparative study of conventional physiotherapy versus robotic-assisted gait training in post-orthopedic injury patients**. *Clinical Rehabilitation, 32*(10), 1404–1414. https://doi.org/10.1177/0269215518777410
2. Bertomeu-Motos, A., Lledó, L. D., Díez, J. A., Catalán, J. M., Ezquerro, S., Badesa, F. J., & García-Aracil, N. (2018). **A review of exoskeletons for rehabilitation of lower limbs**. *Applied Sciences, 8*(12), 2593. https://doi.org/10.3390/app8122593
3. Buesing, C., Fisch, G., O'Donnell, M., Shahidi, I., Thomas, L., Mummidisetty, C. K., … Jayaraman, A. (2015). **Effects of a wearable exoskeleton stride management assist system on gait parameters in chronic stroke: A randomized controlled trial**. *Journal of NeuroEngineering and Rehabilitation, 12*, 69. https://doi.org/10.1186/s12984-015-0067-0
4. Calabrò, R. S., Cacciola, A., Bertè, F., Manuli, A., Leo, A., Bramanti, P., & Naro, A. (2016). **Robotic gait rehabilitation and substitution devices in neurological disorders: Where are we now?** *Neurological Sciences, 37*(4), 503–514. https://doi.org/10.1007/s10072-016-2474-4
5. Chang, S. R., & Kim, Y. H. (2013). **Robotic-assisted gait training in stroke rehabilitation: A systematic review**. *Journal of Rehabilitation Medicine, 45*(6), 517–524. https://doi.org/10.2340/16501977-1146

6. Dollar, A. M., & Herr, H. (2008). **Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art**. *IEEE Transactions on Robotics, 24*(1), 144–158. https://doi.org/10.1109/TRO.2008.915453
7. Esquenazi, A., Talaty, M., Packel, A., & Saulino, M. (2012). **The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury**. *American Journal of Physical Medicine & Rehabilitation, 91*(11), 911–921. https://doi.org/10.1097/PHM.0b013e318269d9a3
8. Hesse, S., Werner, C., Uhlenbrock, D., von Frankenberg, S., Bardeleben, A., & Brandl-Hesse, B. (2001). **An electromechanical gait trainer for restoration of gait in hemiparetic stroke patients**. *Stroke, 32*(8), 1860–1865. https://doi.org/10.1161/01.STR.32.8.1860
9. Krebs, H. I., Hogan, N., Aisen, M. L., & Volpe, B. T. (1998). **Robot-aided neurorehabilitation**. *IEEE Transactions on Rehabilitation Engineering, 6*(1), 75–87. https://doi.org/10.1109/86.662623
10. Louie, D. R., & Eng, J. J. (2016). **Powered robotic exoskeletons in post-stroke rehabilitation of gait: A scoping review**. *Journal of NeuroEngineering and Rehabilitation, 13*, 53. https://doi.org/10.1186/s12984-016-0162-5
11. Louie, D. R., & Eng, J. J. (2016). **Powered robotic exoskeletons in clinical practice: Gait training and rehabilitation post-injury**. *Archives of Physical Medicine and Rehabilitation, 97*(6), 1035–1043. https://doi.org/10.1016/j.apmr.2015.11.021
12. Mehrholz, J., Thomas, S., & Werner, C. (2017). **Electromechanical-assisted training for walking after stroke**. *Cochrane Database of Systematic Reviews*, (5), CD006185. https://doi.org/10.1002/14651858.CD006185.pub4
13. Miller, L. E., Zimmermann, A. K., & Herbert, W. G. (2016). **Clinical effectiveness and safety of powered exoskeleton-assisted walking in patients with spinal cord injury: Systematic review**. *Medical Devices: Evidence and Research, 9*, 455–466. https://doi.org/10.2147/MDER.S103102
14. Molteni, F., Gasperini, G., Cannaviello, G., & Guanziroli, E. (2018). **Exoskeleton and end-effector robots for upper and lower limb rehabilitation: Narrative review**. *PM&R, 10*(9 Suppl 2), S174–S188. https://doi.org/10.1016/j.pmrj.2018.06.005
15. Papadopoulos, E. C., & Khan, S. N. (2004). **Biomechanics of fractures and fracture fixation**. *Orthopedic Clinics of North America, 35*(4), 461–475. https://doi.org/10.1016/j.ocl.2004.06.002
16. Poli, P., Morone, G., Rosati, G., & Masiero, S. (2013). **Robotic technologies and rehabilitation: New tools for rehabilitation after orthopedic injuries**. *European Journal of Physical and Rehabilitation Medicine, 49*(6), 789–800.
17. Rasmussen, J., de Zee, M., Damsgaard, M., Christensen, S. T., Marek, C., & Siebertz, K. (2009). **A general method for scaling musculoskeletal models**. *Journal of Biomechanics, 42*(9), 1354–1360. https://doi.org/10.1016/j.jbiomech.2009.03.017
18. van Dijsseldonk, R. B., Rijken, H., van Nes, I. J. W., van de Meent, H., & Keijsers, N. L. W. (2017). **A framework for selecting exoskeletons in rehabilitation**. *Journal of NeuroEngineering and Rehabilitation, 14*, 62. https://doi.org/10.1186/s12984-017-0261-4
19. Yang, A., Asselin, P., Knezevic, S., Kornfeld, S., & Spungen, A. M. (2015). **Assessment of in-hospital walking velocity and level of assistance in patients with spinal cord injury using a powered exoskeleton**. *Topics in Spinal Cord Injury Rehabilitation, 21*(2), 100–109. https://doi.org/10.1310/sci2102-100
20. Zanotto, D., Lenzi, T., Stegall, P., & Agrawal, S. K. (2013). **Improving transparency of powered exoskeletons using force feedback**. *IEEE Transactions on Robotics, 29*(4), 991–1004. https://doi.org/10.1109/TRO.2013.2260694

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