EXOSKELETONS IN NEUROLOGICAL REHABILITATION: A COMMENTARY ON CURRENT EVIDENCE AND FUTURE DIRECTIONS

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Abstract. Neurological disorders like stroke and spinal cord injury (SCI) are among the leading causes of long-term disability worldwide, causing severe physical, emotional, and economic burdens to patients, families, and healthcare systems. While conventional forms of rehabilitation like physical therapy are the foundation of restoration, they are often limited by resource constraints, variability in delivery, and inaccessibility problems. Robot exoskeletons have emerged as revolutionary technology in neurorehabilitation by allowing for high-intensity, repetitive and task-specific training that enables neuroplasticity and recovery of function. This commentary pertains to the increasing application of exoskeletons to promote mobility, autonomy, and quality of life in patients with stroke and SCI. Clinical trials suggest noteworthy gait speed, endurance, balance, strength, cardiovascular, and psychological resilience gains. But these challenges, such as high cost, heterogeneity of devices, short-term data constraints, and ethical challenges of equity and informed consent, must be overcome. Greater integration into public health systems could reduce disability burden, enhance access to rehabilitation, and enhance outcomes in a variety of populations. Future advances include the development of cost-effective, transportable models, customized therapy protocols, and large clinical trials to enable widespread clinical application. With strategic collaboration and continuous innovation, exoskeletons are set to leave a strong footprint on the neurological rehabilitation horizon of the future.
Keywords: *exoskeleton-assisted rehabilitation, neurological disability, stroke and spinal cord injury, gait training and mobility, neuroplasticity and functional recovery*

Introduction

Millions of people worldwide suffer from neurological disorders like stroke and spinal cord injury (SCI), which are among the main causes of long-term impairment and place a heavy strain on families, carers, and healthcare systems (Banyai and Brișan, 2024). Stroke continues to be a major public health concern, affecting more than 100 million people worldwide. Many stroke survivors experience severe motor impairments, with approximately 70% exhibiting reduced walking speed and capacity, while around 20% relying on a wheelchair for mobility (Wen et al., 2024). Though less common, SCI is equally life-altering, affecting over 20.6 million individuals worldwide and often resulting in profound motor and sensory deficits that significantly hinder daily life and independence (Ullah et al., 2023). Physical therapy and neurorehabilitation exercises are traditional rehabilitation strategies aimed to support motor recovery by fostering neural plasticity and functional adaptation. However, reliance on trained professionals, the necessity for continuous patient commitment and variable effectiveness depending on individual factors, are some limitations present in these approaches (Wen et al., 2024). The development of robotic-assisted rehabilitation technologies provides encouraging

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solutions to address these limitations, especially with the use of exoskeleton-a powered, wearable robotic device. Exoskeletons are used to deliver mechanical support to patients with disabilities, allowing them to receive repetitive, high-intensity gait training and functional exercises in rehabilitation. It augments the neuroplasticity of patients by allowing controlled movement patterns, thus improving functional recovery and mobility (Lee et al., 2024; Gupta et al., 2023; Chang and Kim, 2013). This commentary addresses the contribution of exoskeleton to neurological rehabilitation and, more particularly, their effects on those recovering from stroke and SCI. It explores both the advantages and limitations of this new technology while providing some perspective on future research and clinical implementation.

The burden of neurological disability

Stroke and SCI affect individuals across diverse age groups and backgrounds, presenting profound health challenges to both patients and their communities. With more than 12.2 million new cases recorded each year, stroke continues to be the leading cause of death and permanent disability. Approximately 143 million disability-adjusted life years (DALYs) are lost globally as a result of the related disabilities (Singh et al., 2021). While stroke is commonly linked with aging, the rising incidence among individuals under 50 is an increasing concern. This trend is largely attributed to metabolic, behavioural, and environmental risk factors such as obesity, hypertension, desk-bound routine, and poor dietary habits (Ramli et al., 2021). Similarly, SCI poses significant challenges on patients and healthcare providers, particularly concerning independence and quality of life. Through less common than stroke, its impact can be severe, with incidence rates peaking between ages of 50 and 54 and men being disproportionately affected (Ullah et al., 2023). National Spinal Cord Injury Statistical Center (NSCISC) reports that the most common etiologies of SCI are traumatic events such as vehicular accidents (37.7%), falls (31.4%), and violence (15.3%), with non-traumatic events such as tumours and degenerative diseases also playing a role (Furlan et al., 2022). These injuries cause motor and sensory impairment, usually cause permanent dependence on assistive devices, caregivers, and rehabilitation interventions, and thus require timely intervention strategies. The comparative burden of stroke and SCI is summarized in *Table 1*, highlighting key epidemiological and functional implications of both conditions.

***Table 1**. Key epidemiological and functional implications of the global burden of neurological disabilities: Stroke vs Spinal Cord Injury.*

Parameter	Stroke	Spinal cord injury
Global prevalence	>100 million people	~20.6 million people
Annual new cases	12.2 million+	Not specified (peak: age 50–54)
Common age group	Increasing in <50 years	50–54 years
Common causes	Lifestyle, metabolic risks	Trauma (e.g., vehicle, falls)
DALYs lost globally	~143 million	Not specified
Assistive needs	70% impaired gait; 20% wheelchair	High dependence on mobility aids

Exoskeletons in neurological rehabilitation

In neurological rehabilitation, robotic exoskeletons have become a game-changing instrument that presents new opportunities for enhancing movement and regaining independence. These devices are generally categorized into end-effector systems and exoskeleton-based models, with varying levels of assistance ranging from fully powered designs to assist-as-needed configurations (Nepomuceno et al., 20224; Zhang et al., 2024). Studies have gained extensive attention regarding the potential of lower-limb exoskeletons, such as ReWalk, Ekso, Indego, and Lokomat, in gait training and mobility restoration. These technologies facilitate rehabilitation exercises such as standing, weight-bearing activities, and assisted walking, ultimately improving motor learning and functional recovery (Zhang et al., 2024; Ramli et al., 2021). Emerging data indicates that exoskeletons may also help people with other neurological diseases like Parkinson's disease, muscular dystrophy, and traumatic brain injury, even though the majority of research has focused on their use in stroke and SCI rehabilitation (Gryfe et al., 2022; Estilow et al., 2018; Nolan et al., 2018).

Potential benefits of exoskeletons

There have been many reports on substantial improvements of gait metrics, such as walking speed, endurance, and balance after exoskeleton-assisted rehabilitation, which has proved psychological and physical benefits (Zhang et al., 2024; Edwards et al., 2022). For instance, Edwards and colleagues showed that after a 12-week exoskeleton intervention, gait speed increased by 51%, the 6-minute walk test distance improved by 34%, and the Timed Up and Go test increased by 18.7% (Edwards et al., 2022). Further demonstrating its ability to improve mobility and general function, *Figure 1* illustrates the advantages of exoskeleton-assisted rehabilitation in neurological diseases. Beyond mobility gains, exoskeleton use has been associated with increased muscle strength, improved cardiovascular health and enhanced bone density (He et al., 2024; Van Dijsseldonk et al., 2023; 2020; Charbonneau et al., 2022). Additionally, some studies have also demonstrated potential benefits in alleviating neuropathic pain and fatigue, concurrently improving patients' overall quality of life (Van Nes et al., 2024). Furthermore, the psychological impact is also noteworthy, as increased confidence, motivation and hope for recovery are outlined by many users. These findings underscore the multifaceted benefits of exoskeletons, not only in promoting mobility, but also in fostering overall well-being and supporting social reintegration (Gupta et al., 2023; Charbonneau et al., 2022).

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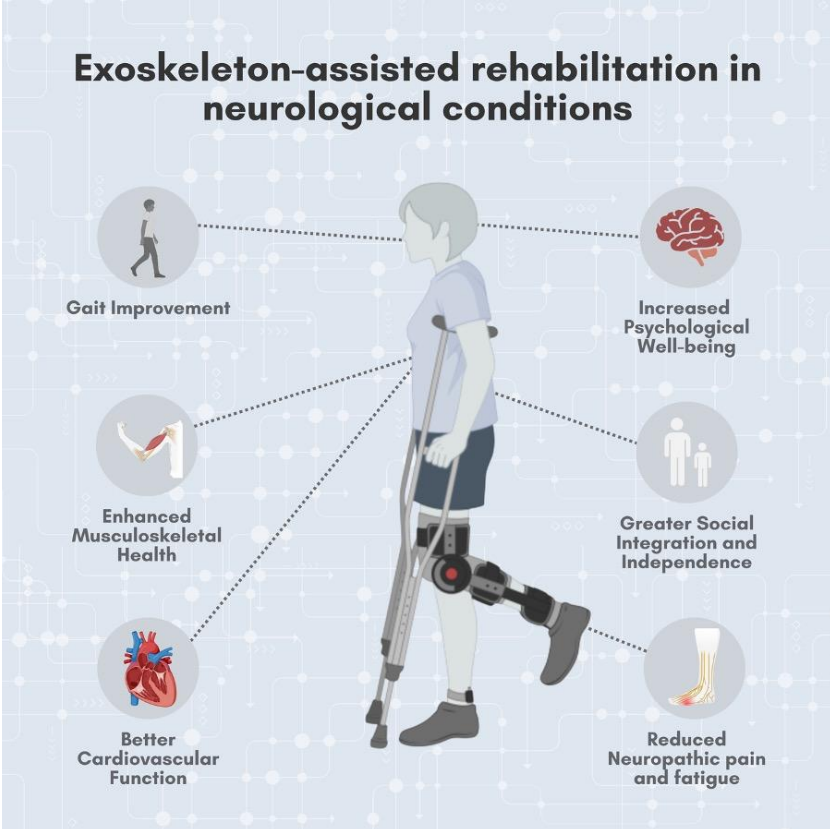

Figure 1. *Benefits of exoskeleton-assisted rehabilitation in neurological conditions.*

Challenges and limitations

A number of obstacles prevent exoskeletons from being widely used, despite their potential. The generalisability of results is hindered by the small sample numbers, lack of control groups, or short follow-up periods of many studies (Nepomuceno et al., 2024; Aach et al., 2023). Moreover, variations across different devices and rehabilitation protocols complicate research comparisons and clinical applications (Hsu et al., 2023; Calabrò et al., 2021). Safety concerns such as skin irritation and discomfort have also been noted (Aach et al., 2023; Gil-Agudo et al., 2023). Furthermore, the substantial costs and accessibility challenges further restrict their widespread clinical integration (Wolff et al., 2024; Gupta et al., 2023). *Figure 2* illustrates the current challenges and future directions of exoskeletons in neurological rehabilitation, providing an overview of key barriers and potential solutions. Additionally, *Table 2* presents a summary of the clinical benefits and associated limitations of exoskeleton-assisted rehabilitation. The side-by-side comparison is intended to put into perspective the overall implications for healthcare systems and future research directions.

Table 2*. Summary of reported clinical benefits and identified challenges of exoskeleton-assisted rehabilitation.*

Category	Specific aspect	Details	References
Clinical benefits	Gait speed improvement	↑ 51% after 12-week training	Edwards et al. (2022)
	6-minute walk test	↑ 34% improvement	Edwards et al. (2022)
	Timed Up and Go (TUG)	↑ 18.7% improvement	Edwards et al. (2022)
	Muscle strength	Increased post-training	He et al. (2024)
	Cardiovascular and bone health	Improved markers	Van Dijsseldonk et al. (2020)
	Quality of life, motivation, self-	Enhanced psychological	Gupta et al. (2023)

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	efficacy	outcomes	
Challenges	Study design limitations	Small sample size, lack of control groups, short follow-ups	Nepomuceno et al. (2024)
	Device and protocol variability	Difficult to compare across different models and regimens	Hsu et al. (2023)
	Physical side effects	Skin irritation, discomfort	Aach et al. (2023)
	Cost and accessibility	High expense; limited use in low- and middle-income countries	Gupta et al. (2023)
	Clinical integration	Need for training, infrastructure mismatch	Calabrò et al. (2021)

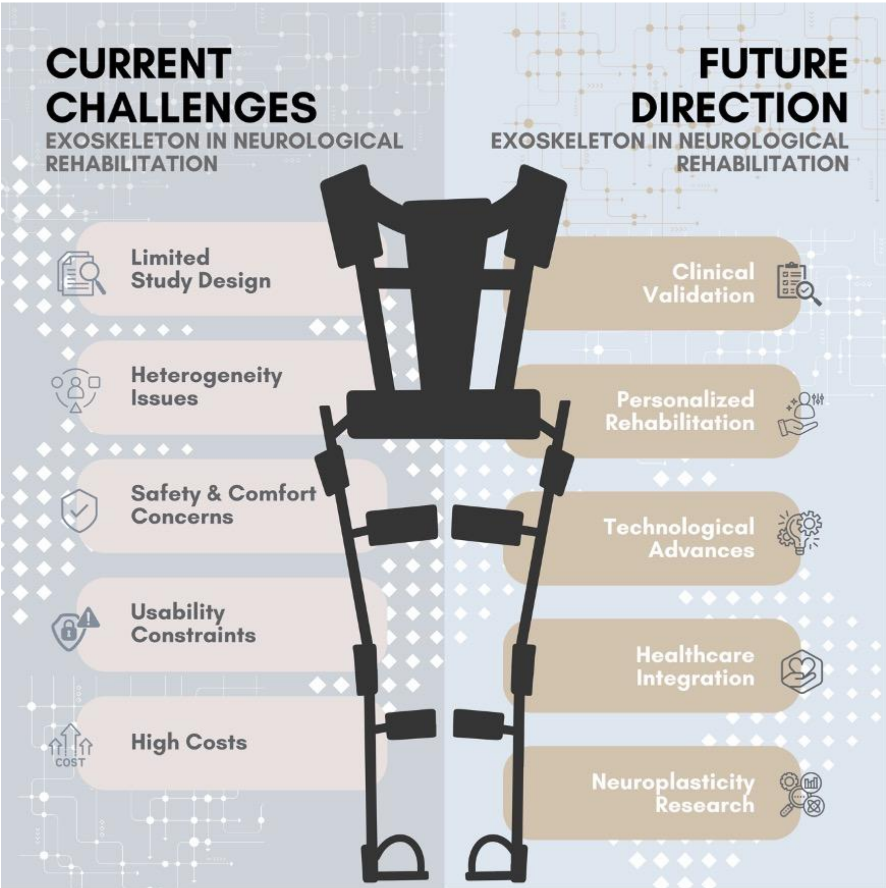

Figure 2. *Current challenges and future directions of exoskeletons in neurological rehabilitation.*

Public health implications

The integration of exoskeletons into neurorehabilitation protocols is not only of individual value but has substantive public health implications. As the global population ages and the burden of neurological disease increases, economic and healthcare burden from handling prolonged disability will become magnified (Singh et al., 2021). Exoskeleton rehabilitation offers a promising path to alleviating this burden by enabling earlier recovery, reducing dependency on caregivers, and even reducing hospitalization stays and readmission (Wolff et al., 2014). Exoskeleton-based rehabilitation in community settings can also reduce disparities in health, especially when complemented by mobile and cost-effective designs to accommodate lower-resource settings (Gupta et al., 2023). Furthermore, large-scale use can fuel improvements in rehabilitation

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guidelines, infrastructure development, and workforce competencies, generating systemic reform in the way post-stroke and SCI rehabilitation are conducted. By integrating technological innovation with public health approaches, exoskeletons could be an essential instrument in redefining extended-term neurological treatment.

Ethical and social considerations

With exoskeletons increasingly used in clinical and rehabilitation environments, social and ethical concerns must be met to ensure equitable and responsible implementation. Accessibility is a primary concern, particularly in low- and middle-income countries where the device's high expense and limited infrastructure could exacerbate current health inequities (Gupta et al., 2023). Moreover, user autonomy and informed consent must be preserved, especially in users with cognitive or communication impairments. Psychological impacts, such as unrealistic anticipation or dependency on assistive technology, also have to be managed through professional patient education and counseling (Van Nes et al., 2024). At a societal level, the integration of these technologies raises issues concerning inclusion, workforce training, and replacing traditional therapy roles. Resolution of such issues in advance through policy making, stakeholder engagement, and interdisciplinary study will be essential in the pursuit of ensuring that the application of exoskeletons ensures both ethical integrity as well as social inclusiveness in rehabilitation practice. These ethical and social issues are summarized in *Table 3* to provide a structured overview for policy and clinical consideration.

***Table 3**. Policy and clinical consideration of the global burden of neurological disabilities: Stroke vs Spinal Cord Injury.*

Consideration category	Specific issues	Recommendations
Accessibility	Cost barriers, urban-rural divide	Subsidy, localized production
Autonomy and consent	Cognitive/communication impairment	Enhanced consent protocols
Psychological impact	Unrealistic expectations, dependency	Pre-use counseling
Workforce & policy	Displacement of therapists, training needs	Multi-stakeholder engagement, education

Future directions

Despite their promise, the clinical translation landscape of exoskeletons in neurological rehabilitation is still in its infancy, warranting large-scale and long-term trials to provide clearer evidence of their utility in such settings. This predictive approach could be complemented with individual tailoring of rehabilitation strategies that are specific to the needs presented by each patient. Additionally, studying neuroplasticity can help optimize treatment plans and create more effective interventions. Light, portable, and affordable exoskeletons ought to be developed for usability and economic reasons. Partnership of researchers, physicians, and industries in accelerating innovation with translation of research to clinical practice is important. Comprehensive cost-effectiveness studies will help in mainstreaming exoskeletons within clinical use and health regulations.

Conclusion

Exoskeleton-assisted therapy is a game-changing strategy for improving mobility and quality of life in patients with neurological disorders. Future studies are required to optimise these technologies and guarantee their successful integration into clinical

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practice, even though the available data indicates encouraging advantages. Current limitations have to be addressed with rigorous scientific investigation, including rehabilitation strategies tailored to individual needs, and ongoing technological innovation, which will help facilitate broader clinical adoption and improved patient outcomes. With increased development and collaboration between disciplines, exoskeletons have the potential to be at the heart of any future rehabilitation process, reestablishing the individuals' independence and general well-being.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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