**Medical Science**

**To Cite:**
Gołacki R, Świta M, Procajło K, Szewczyk J. The Role of Lower Limb Exoskeletons in the Rehabilitation of Gait Disorders: A Review. *Medical Science* 2025; 29: e130ms3623
doi: https://doi.org/10.54905/disssi.v29i162.e130ms3623

**Authors' Affiliation:**
[1]Medical University of Lublin, al. Racławickie 1, 20-059 Lublin, Poland

***Corresponding author:**
Rafał Gołacki, Medical University of Lublin, al. Racławickie 1, 20-059 Lublin, Poland
E-mail: rgolacki00@gmail.com

**Peer-Review History**
Received: 03 July 2025
Reviewed & Revised: 09/July/2025 to 01/August/2025
Accepted: 07 August 2025
Published: 18 August 2025

**Peer-review Method**
External peer-review was done through double-blind method.

Medical Science
pISSN 2321–7359; eISSN 2321–7367



DISCOVERY SCIENTIFIC SOCIETY

# The Role of Lower Limb Exoskeletons in the Rehabilitation of Gait Disorders: A Review

**Rafał Gołacki[1*], Michał Świta[1], Katarzyna Procajło[1], Julia Szewczyk[1]**

## ABSTRACT

Introduction: Gait disturbances resulting from lower limb dysfunctions cause meaningful changes in the lives and independence of older adults, and the number of people affected by this problem will continue to increase in the future. Rehabilitation is the only effective method of helping patients affected by this problem. Exoskeletons are gaining value in rehabilitation, boosting safety and rehabilitation effectiveness. This article aims to assess exoskeletons, examine the utility resulting from their use, and evaluate the prospects for their further application. Methodology: Between April and June 2025, we executed a literature review using databases such as Google Scholar and PubMed. Keywords included 'rehabilitation,' 'exoskeleton,' 'lower limb,' and 'dysfunction.' We selected articles published between 2017 and 2025 based on their relevance to the use of lower limb exoskeletons in rehabilitation, and also included key earlier studies. Two reviewers analyzed and selected studies with a focus on clinical trials and systematic reviews. Result and Discussion: Researchers demonstrated in their studies that robotic exoskeletons enhance balance, gait symmetry, step length, and neuroplasticity in patients affected by stroke, spinal cord injuries, and multiple sclerosis. Clinical trials demonstrate significant functional gains compared to conventional rehabilitation. Adverse effects of exoskeleton use included fatigue, skin abrasions, and orthostatic problems; however, these were considered safe during rehabilitation. While they offer numerous benefits, there is still a lack of large-scale studies confirming all the benefits of their use. The most critical challenges facing exoskeletons are ensuring patient safety and adapting them to individual needs.

**Keywords**: rehabilitation, exoskeleton, dysfunction, lower limb, injury

## 1. INTRODUCTION

Sustaining a proper gait is one of the most essential elements for appropriate functioning. Dysfunctions of walking, which are especially common in older people, can lead to problems with everyday functioning and compound the risk of falling (Baker, 2018). Among older adults, the proportion of individuals with abnormal gait rises with age. Researchers divide the causes of walking disorders into two groups (Ataullah & De Jesus, 2025). Neurological causes are more common and include neurodegenerative diseases, stroke, sensory disorders, and myelopathies. Among the non-neurological causes, we can distinguish degenerative joint disease, injuries, muscle disorders, circulatory and vascular diseases, and psychogenic disorders (Lam, 2011; Cicirelli et al., 2022).

Gait disturbances may be a significant element that complicates the patient's functioning. Prompt and effective recovery of walking precipitates the patient's return to social and professional life. Proper rehabilitation is therefore essential. Early initiation of rehabilitation in stroke patients may bring positive results in improving the motor function of the lower limbs and restoring normal gait (Coleman et al., 2017). The beginning of gait rehabilitation at the initial stages of Parkinson's disease has positive effects. Such actions may be beneficial in alleviating motor symptoms and delaying the onset of gait problems (Ellis et al., 2021). The rehabilitation of patients with walking disorders requires solutions to improve this process. One relatively new tool in this field is robotic exoskeletons. Thanks to them, we can have more control over the rehabilitation process, reduce the burden on physiotherapists, and better assess the progress and return of function in patients (Rodriguez-Fernandez et al., 2021; Plaza et al., 2023).

Our work aims to summarize the current knowledge about several lower limb exoskeletons and compare their strengths and limitations in the rehabilitation of patients with walking disabilities.

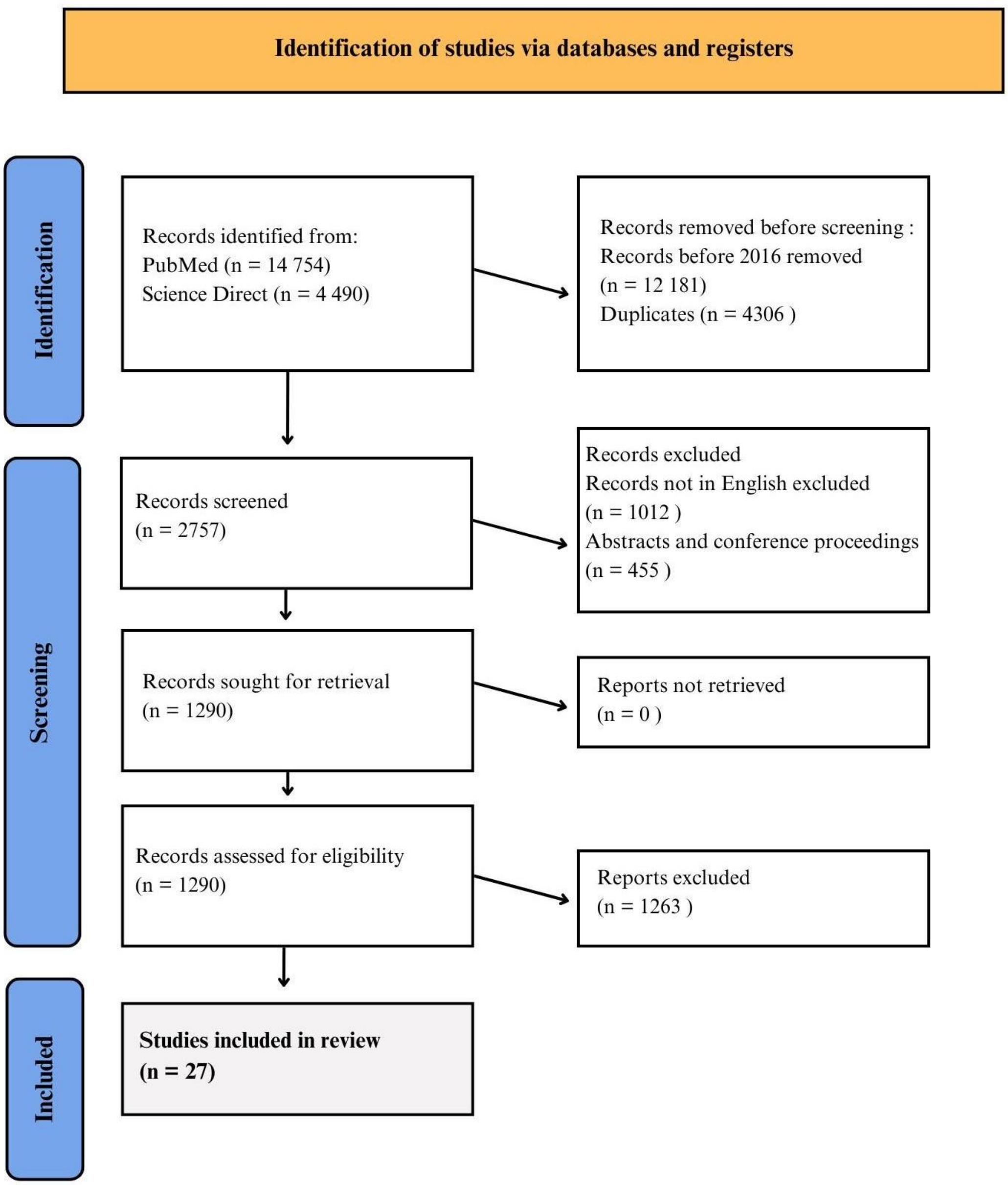


**Fig 1**. PRSIMA consort chart of selected studies.

## 2. REVIEW METHODS

The authors did a literature review between April and June 2025, using databases such as Google Scholar and PubMed. We searched for relevant papers using keywords separately and in combinations. The terms were entered in individual databases individually and in combination. We checked the titles and abstracts to select documents related to our topic. We rejected those that did not meet these criteria. The assessment of articles was performed independently by two people. The inclusion criteria concerned studies and reviews of papers that focused on the use of lower limb exoskeletons in the rehabilitation of patients with lower limb dysfunction. We focused on studies published from 2017 onwards, with some key works from earlier periods also. We created the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) diagram (Figure 1).

## 3. RESULTS AND DISCUSSION

**Structure of exoskeletons**

Exoskeletons are mechanical devices that aid users in improving mobility, endurance, and strength. They have found application in the military but are also particularly important in medical rehabilitation (Hussain et al., 2021). The lower limb exoskeleton is a metal structure that has a drive motor installed at the hip and knee joints. The system analyzes parameters such as joint angles and angular velocity, controlling movement in real-time (Li et al., 2023). There are two types of exoskeletons, depending on how they work. The first completely replaces the patient's limbs. The second helps during rehabilitation because it supports the limbs rather than replacing them like the first type (Baud et al., 2021).

**History and Development of Exoskeleton Technology**

In 1960, General Electric developed the first electrically powered exoskeletons, including the Hardiman suit. The developers of this device designed it to increase human strength using hydraulics. Despite its mechanical complexity and promise, the Hardiman was impractical due to its weight. In the 2000s, defense-related interest led to the development of lighter, battery-powered systems such as the HULC (Human Universal Load Carrier). They designed it to allow soldiers to lift to 90 kg with minimal effort. The transition of exoskeleton technology from military to medical use was a significant development in the field. One of the first big successes was the Hybrid Assistive Limb (HAL), created by Professor Yoshiyuki Sankai in Japan. HAL was one of the first exoskeletons used in rehabilitation after conditions like stroke or spinal cord damage affecting motor function.

What made HAL special was how it listened to the body. It could pick up tiny signals from the skin—signals that showed the person wanted to move—and then used motors in the suit to help make that movement happen. This was groundbreaking—for the first time, it was no longer just about moving another person's body but about assisting them to move independently, using their own effort.

Modern exoskeletons are now smaller, more efficient, and easier to use than ever before. Devices like ReWalk, EksoGT, Indego, and ExoAtlet now support rehabilitation not only in hospitals and specialized centers but also in homes worldwide (Molteni et al., 2018). They are most commonly helping people with learning to walk again after spinal cord injuries, getting up and moving early after a stroke, and supporting rehabilitation in conditions like multiple sclerosis and cerebral palsy.

Modern exoskeletons integrate advanced software with motion and muscle sensors to improve user support. This combination enables more symmetrical gait patterns and reduces compensatory movements. Another exciting direction is using brain-computer interfaces supported by AI algorithms, which could help exoskeletons better react to the user's movements as they happen (Table 1) (Calabro et al., 2018).

**Comparison of the most common exoskeletons**

**Table 1**. Comparison of the most common exoskeletons.

| Device | Clinical Indication | User Profile | Control interface | Assisted segments | Clinical outcomes |
|---|---|---|---|---|---|
| *Lokomat*® Hocoma Switzerland (Zhang et al., 2022) | Stroke, Spinal cord injury (SCI), Cerebral Palsy (CP) | stationary clinical patient | Computer, therapist | Hips and knees on the treadmill | Improved gait symmetry |

| | | | | | |
|---|---|---|---|---|---|
| *EksoNR®* Ekso Bionics USA (Wiśniowska-Szurlej et al., 2023) | Stroke, SCI, Multiple Sclerosis (MS), brain injury. | Partial/complete lower limb paralysis, | Sensors, therapist | Full lower limbs (LL) | Improved step length |
| *ReWalk*® Lifeward USA (Hong et al., 2020) | Paraplegia SCI | Complete lower limb paralysis | control system, motion sensors | Full LL | Increased independent ambulation |
| *Indego®* Ekso Bionics USA (Tefertiller et al., 2018) | Stroke, SCI | Clinic, and home | Motion sensors, app | Hips and knees | Improved gait speed |
| *Keeogo®* B-Temia Canada (McGibbon et al., 2018) | MS, muscular dystrophy, CP | Partial leg strength, | EMG, motion sensors | Knees | Enhanced endurance in MS patients |
| *HAL®* Cyberdyne Japan (Aach et al., 2023) | Stroke, SCI, neuromuscular disease | Clinical | Autonomous gait, joystick | Full LL | Gait function gains in stroke patients |
| *Atalante®* Wandercraft France (Lejeune et al., 2025) | CP, MS, SCI | Clinic patient | EMG = biofeedback, sensors | Full LL | Improving independent walking |

Spinal cord injury (SCI) leads to motor dysfunction. Proper rehabilitation and restoration of these functions reduce the risk of dangerous complications. These interventions allow patients to return to physical activity and improve their daily quality of life. Because hospital rehabilitation is often limited, portable therapy devices are essential for helping patients regain function. Exoskeletons used by such patients in home activities not only facilitate daily functioning but also reduce muscle contractures and joint stiffness (He et al., 2024).

Stroke is one of the most common causes of gait disorders. Regaining the ability to walk in such patients is one of the most critical tasks of rehabilitation. However, a large percentage of patients are still unable to regain this ability after therapy. Exoskeletons are becoming a tool that helps meet the rehabilitation needs of patients. Exoskeleton-assisted walking therapy supports more efficient neuronal recuperation by involving the nervous system in functional movement. This type of therapy is comparable to conventional stroke rehabilitation and may even be more effective (Louie & Eng, 2016).

Nowadays, exoskeletons are helping an increasingly wider group of patients with impaired lower limb function. The fundamental question is whether such therapy is as effective as traditional rehabilitation and whether robotic systems can fully replace conventional methods or serve only as a complementary tool.

In a study by Huo et al., (2024), stroke patients who trained with an exoskeleton on one side of the body regained better balance and stability while walking than those in standard therapy. The researchers indicate that using the exoskeleton may have the advantage of a more coordinated gait pattern.

A key goal in stroke rehabilitation is to enhance neural conduction in the brain and spinal cord. Tao et al., (2023) and Yoo et al., (2025) provide evidence that the use of exoskeletons in rehabilitation promotes neuroplasticity, leading to improved movement and leg mobility. The study by Zhang et al., (2024), examines the use of combined robotic and classical therapy, shows its advantages over upright bed rehabilitation for stroke patients (Table 2). The use of exoskeletons in rehabilitation must always be safe for patients. Adverse events, including falls, abrasions, and pain, are possible, but their impact on safety is currently marginal. Therefore, it is necessary to report any side effects and eliminate them.

Although exoskeletons are relatively new, current research suggests they are safe for use in rehabilitation. One of the benefits listed is the reduced need to use additional assistive devices during walking. Currently conducted studies focus on small groups of patients; therefore, it is challenging to state whether these devices are safe clearly (Gil-Agudo et al., 2023; Zhang et al., 2024; Aach et al., 2023).

**Table 2**. Analysis of research and rehabilitation results of patients using lower limb exoskeletons.

| Author | Study design | Study population | Method | Results |
|---|---|---|---|---|
| Huo et al., 2024 | Randomized single-anonymized clinical trial. | Researchers divided forty patients with subacute stroke into two groups: interventional, assisted by a robot, and control, with the need for rehabilitation. | Researchers collected measurements in both groups at baseline and again after the second and fourth weeks of therapy. The main assessments were balance and gait. | A study demonstrated that the implemented framework significantly enhances balance and gait in patients following subacute stroke. |
| Fan et al., 2025 | Randomized double-masked clinical trial. | Twenty-five stroke patients: 13 in the exoskeleton group and 12 in the conventional rehabilitation group. | In both groups, central conduction, lower limb function, and gait parameters were assessed before the intervention and again at 2 and 4 weeks. | Studies have shown that the use of the robot has a positive impact on cerebral cortex activity and nerve conduction in the spinal cord. |
| Yoo et al., 2023 | Prospective randomized controlled trial. | The researchers divided thirty patients with chronic stroke into two groups of fifteen, each of which underwent four weeks of training. The study group used a robot, while the control group trained on a treadmill. | The researchers examined oxyhemoglobin levels, lower limb function parameters, and gait. | Robotic gait training has a beneficial effect on cortical modulation, improves the spatial step symmetry coefficient, and lowers limb function parameters. |
| Gil-Agudo et al., 2023 | Randomized controlled trial. | Twelve patients with C2-C4 spinal cord injuries completed fifteen sessions of gait training using a lower limb exoskeleton, while eleven similar patients formed the control group. | Researchers assessed patients' safety by recording adverse events and evaluating skin lesions, pain, and fatigue. | The exoskeleton met safety requirements, and the patients rated it well. |
| Zhang et al., 2024 | Pilot, single-masked, randomized controlled trial. | The study included 24 patients with acute stroke, divided into two groups of 12 each. The first group underwent rehabilitation on a vertical bed, and the second used an exoskeleton. | The study assessed balance, lower limb motor function, posture, and basic daily activities. | The exoskeleton is more effective than rehabilitation in a vertical bed in terms of regaining balance and motor function of the lower limbs. |
| Aach et al., 2023 | Single-center prospective study. | Fourteen women and thirty-six men with acute SCI underwent 12 weeks of exoskeleton-assisted rehabilitation. | The measurements included walking tests, treadmill parameters (speed, distance, time), and lower limb motor functions. | The study confirms the effectiveness and practicality of this device during training in patients with spinal cord injury. |

## 4. CONCLUSION

Lower-limb exoskeletons represent a promising approach to rehabilitation for individuals with gait impairments caused by illness. They improve walking speed, endurance, and balance. We are waiting to know how long these benefits will last—we need more solid, long-term research to be certain. This type of technology is costly, and only a limited number of centers can afford to implement it; therefore, its implementation is currently complicated. In the future, exoskeletons will be increasingly incorporated into rehabilitation programs. This is due to significant technological advancements in medicine, as well as the involvement of medical professionals. Ultimately, exoskeletons will be a key element of rehabilitation, not just a futuristic concept.

**Author's Contributions**

Conceptualization: Michał Świta, Rafał Gołacki
Methodology: Michał Świta, Rafał Gołacki, Julia Szewczyk
Software: Julia Szewczyk, Katarzyna Procajło
Check: Michał Świta, Rafał Gołacki, Katarzyna Procajło
Formal analysis: Michał Świta, Rafał Gołacki, Julia Szewczyk
Investigation: Michał Świta, Rafał Gołacki,
Resources: Michał Świta, Katarzyna Procajło
Data curation: Michał Świta, Julia Szewczyk, Katarzyna Procajło
Writing - rough preparation: Michał Świta, Rafał Gołacki, Julia Szewczyk, Katarzyna Procajło,
Writing - review and editing: Michał Świta, Rafał Gołacki, Julia Szewczyk, Katarzyna Procajło,
Visualization: Katarzyna Procajło, Julia Szewczyk
Supervision: Julia Szewczyk, Katarzyna Procajło
Project administration: Michał Świta, Rafał Gołacki
All authors reviewed the manuscript and approved its final version for publication.

**Acknowledgments**

The authors have no acknowledgments to disclose.

**Informed consent**

Not applicable.

**Ethical approval**

Not applicable.

**Funding**

This study has not received any external funding.

**Conflict of interest**

The authors declare that there is no conflict of interest.

**Data and materials availability**

All data associated with this work are present in the paper.

## REFERENCES

1. Aach M, Schildhauer TA, Zieriacks A, Jansen O, Weßling M, Brinkemper A, Grasmücke D. Feasibility, safety, and functional outcomes using the neurological controlled Hybrid Assistive Limb exoskeleton (HAL®) following acute incomplete and complete spinal cord injury - Results of 50 patients. J Spinal Cord Med 2023;46(4):574-581. doi:10.1080/10790268.2023.2200362
2. Ataullah AHM, De Jesus O. Gait Disturbances. In: StatPearls. StatPearls Publishing; 2025. http://www.ncbi.nlm.nih.gov/books/ NBK560610/
3. Baker JM. Gait Disorders. Am J Med 2018;131(6):602-607. doi:10.1016/j.amjmed.2017.11.051
4. Baud R, Manzoori AR, Ijspeert A, Bouri M. Review of control strategies for lower-limb exoskeletons to assist gait. J Neuroeng Rehabil 2021;18(1):119. doi:10.1186/s12984-021-00906-3
5. Calabrò RS, Naro A, Russo M, Bramanti P, Carioti L, Balletta T, Buda A, Manuli A, Filoni S, Bramanti A. Shaping neuroplasticity by using powered exoskeletons in patients

with stroke: a randomized clinical trial. J Neuroeng Rehabil 2018;15(1):35. doi:10.1186/s12984-018-0377-8
6. Cicirelli G, Impedovo D, Dentamaro V, Marani R, Pirlo G, D'Orazio TR. Human Gait Analysis in Neurodegenerative Diseases: A Review. IEEE J Biomed Health Inform 2022;26(1):229-242. doi:10.1109/JBHI.2021.3092875
7. Coleman ER, Moudgal R, Lang K, Hyacinth HI, Awosika OO, Kissela BM, Feng W. Early Rehabilitation After Stroke: a Narrative Review. Curr Atheroscler Rep 2017;19(12):59. doi:10.1007/s11883-017-0686-6
8. Ellis TD, Colón-Semenza C, DeAngelis TR, Thomas CA, Hilaire MHS, Earhart GM, Dibble LE. Evidence for Early and Regular Physical Therapy and Exercise in Parkinson's Disease. Semin Neurol 2021;41(2):189-205. doi:10.1055/s-0041-1725133
9. Fan T, Zheng P, Zhang X, Gong Z, Shi Y, Wei M, Zhou J, He L, Li S, Zeng Q, Lu P, Zhao Y, Zou J, Chen R, Peng Z, Xu C, Cao P, Huang G. Effects of exoskeleton rehabilitation robot training on neuroplasticity and lower limb motor function in patients with stroke. BMC Neurol 2025;25(1):193. doi:10.1186/s12883-025-04203-7
10. Gil-Agudo Á, Megía-García Á, Pons JL, Sinovas-Alonso I, Comino-Suárez N, Lozano-Berrio V, Del-Ama AJ. Correction: Exoskeleton-based training improves walking independence in incomplete spinal cord injury patients: results from a randomized controlled trial. J Neuroeng Rehabil 2023;20(1): 160. doi:10.1186/s12984-023-01281-x
11. He Y, Xu Y, Hai M, Feng Y, Liu P, Chen Z, Duan W. Exoskeleton-Assisted Rehabilitation and Neuroplasticity in Spinal Cord Injury. World Neurosurg 2024;185:45-54. doi:10.1016/j.wneu.2024.01.167
12. Hong E, Gorman PH, Forrest GF, Asselin PK, Knezevic S, Scott W, Wojciehowski SB, Kornfeld S, Spungen AM. Mobility Skills With Exoskeletal-Assisted Walking in Persons With SCI: Results From a Three Center Randomized Clinical Trial. Front Robot AI 2020;7:93. doi:10.3389/frobt.2020.00093
13. Huo C, Shao G, Chen T, Li W, Wang J, Xie H, Wang Y, Li Z, Zheng P, Li L, Li L. Effectiveness of unilateral lower-limb exoskeleton robot on balance and gait recovery and neuroplasticity in patients with subacute stroke: a randomized controlled trial. J Neuroeng Rehabil 2024;21(1): 213. doi:10.1186/s12984-024-01493-9
14. Hussain F, Goecke R, Mohammadian M. Exoskeleton robots for lower limb assistance: A review of materials, actuation, and manufacturing methods. Proc Inst Mech Eng H 2021;235(12):1375-1385. doi:10.1177/09544119211032010
15. Lam R. Office management of gait disorders in the elderly. Can Fam Physician 2011;57(7):765-770.
16. Lejeune T, Nuic D, Dehem S, Previnaire JG, Cuenot C, Debugne T, Kaps J, Paul B, Pean V, Perez SS, Juhel F, Tatsidou S, Kerdraon J. Hands-free Atalante exoskeleton in post-stroke gait and balance rehabilitation: a safety study. J Neuroeng Rehabil 2025;22(1):82. doi:10.1186/s12984-025-01621-z
17. Li J, Tai Y, Meng F. Rehabilitation exoskeleton torque control based on PSO-RBFNN optimization. PLoS One 2023;18(8):e0285453. doi:10.1371/journal.pone.0285453
18. Louie DR, Eng JJ. Powered robotic exoskeletons in post-stroke rehabilitation of gait: a scoping review. J Neuroeng Rehabil 2016;13(1):53. doi:10.1186/s12984-016-0162-5
19. McGibbon CA, Sexton A, Jayaraman A, Deems-Dluhy S, Gryfe P, Novak A, Dutta T, Fabara E, Adans-Dester C, Bonato P. Evaluation of the Keeogo exoskeleton for assisting ambulatory activities in people with multiple sclerosis: an open-label, randomized, cross-over trial. J Neuroeng Rehabil 2018;15(1):117. doi:10.1186/s12984-018-0468-6
20. Molteni F, Gasperini G, Cannaviello G, Guanziroli E. Exoskeleton and End-Effector Robots for Upper and Lower Limbs Rehabilitation: Narrative Review PM R. 2018;10(9 Suppl 2):S174-S188. doi:10.1016/j.pmrj.2018.06.005
21. Plaza A, Hernandez M, Puyuelo G, Garces E, Garcia E. Wearable rehabilitation exoskeletons of the lower limb: analysis of versatility and adaptability. Disabil Rehabil Assist Technol 2023;18(4):392-406. doi:10.1080/17483107.2020.1858976
22. Rodríguez-Fernández A, Lobo-Prat J, Font-Llagunes JM. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J Neuroeng Rehabil 2021;18(1):22. doi:10.1186/s12984-021-00815-5
23. Tefertiller C, Hays K, Jones J, Jayaraman A, Hartigan C, Bushnik T, Forrest GF. Initial Outcomes from a Multicenter Study Utilizing the Indego Powered Exoskeleton in Spinal Cord Injury. Top Spinal Cord Inj Rehabil 2018;24(1):78-85. doi:10.1310/sci17-00014
24. Wiśniowska-Szurlej A, Wołoszyn N, Brożonowicz J, Ciąpała G, Pietryka K, Grzegorczyk J, Leszczak J, Ćwirlej-Sozańska A, Sozański B, Korczowski B. Enhanced Rehabilitation Outcomes of Robotic-Assisted Gait Training with EksoNR Lower Extremity Exoskeleton in 19 Stroke Patients. Med Sci Monit 2023;29:e940511. doi:10.12659/MSM.940511
25. Yoo M, Chun MH, Hong GR, Lee C, Lee JK, Lee A. Effects of Training with a Powered Exoskeleton on Cortical Activity Modulation in Hemiparetic Chronic Stroke Patients: A Randomized Controlled Pilot Trial. Arch Phys Med Rehabil 2023;104(10):1620-1629. doi:10.1016/j.apmr.2023.05.012
26. Zhang L, Lin F, Sun L, Chen C. Comparison of Efficacy of Lokomat and Wearable Exoskeleton-Assisted Gait Training in People with Spinal Cord Injury: A Systematic Review and

Network Meta-Analysis. Front Neurol 2022;13:772660. doi:10.3389/fneur.2022.772660

27. Zhang Y, Zhao W, Wan C, Wu X, Huang J, Wang X, Huang G, Ding W, Chen Y, Yang J, Su B, Xu Y, Zhou Z, Zhang X, Miao F, Li J, Li Y. Exoskeleton rehabilitation robot training for balance and lower limb function in sub-acute stroke patients: a pilot, randomized controlled trial. J Neuroeng Rehabil 2024;21(1):98. doi:10.1186/s12984-024-01391-0