Endurance

Many articles that examine exoskeletons look at resulting changes in endurance. Of those articles that were not review articles, 80% utilized the 6 Minute Walk Test (6MWT) to measure endurance. Other measurements used were the 2 Minute Walk Test (2MWT), six minute arm cycle, and the 30 Minute Walk Test (30MWT). The majority evaluated subjects with spinal cord injury (37 articles) followed by stroke (17 articles). There were 32 case series or studies, followed by 19 review articles, and 10 randomized controlled articles. Of studies that utilized a single device, Ekso1.1/GT/NR device, referred to as "Ekso" in this paper, was used the most (25 articles), followed by ReWalk (9).

Studies completed in IP Rehab

Research completed in a lab setting is often challenging to recreate in a clinic environment, and therefore research completed in a clinical setting is typically more meaningful to clinicians. One such study was conducted at 3 inpatient rehabilitation hospitals in Canada where patients with subacute stroke (CVA) who were unable to walk without substantial assistance were randomized to receive exoskeleton or standard physical therapy until discharge, replacing 75% of sessions. When assessed as-treated, the group that received exoskeleton training was able to walk further at discharge, though this was not statistically significant, and at 6 month follow-up, which was statistically significant.[1] At 6 month follow up, the Ekso group completed an average of 211.2 m over 6 minutes, while the usual care group was able to complete less than half of that distance at 103.0 m.[1] In an acute rehabilitation facility, 22 patients were provided with at least 3 sessions of Ekso training during their length of stay, and these patients were compared with historical matched controls. Distance was measured during each physical therapy session and it was found that during standard of care sessions, there was no difference between groups, but during Ekso sessions, the Ekso group walked significantly further (83.2m) than the control group (48.99m) who only received standard of care therapy.[2] A similar result was found in 14 participants who walked a further distance in Ekso sessions versus standard of care sessions. Improvement in 6MWT distance and speed was seen, and the magnitude of improvement was moderately correlated with the number of robotic training sessions.[3]

Spinal Cord Injury (SCI)

Multiple randomized controlled trials exist that utilize subjects with SCI and examine the effects of an exoskeleton on gait endurance. In one, nine individuals were randomly assigned to receive exoskeleton or conventional gait training daily for 3 weeks. Significant improvement in the 6MWT was seen only in the exoskeleton group who improved from 50 m to 67 m post intervention, while the control group improved insignificantly from 147 m to 154 m.[4] Another study compared Ekso to body weight support treadmill training (BWSTT) to passive controls, and found that while each group improved their 6MWT distance over the 12 week intervention, the amount of improvement differed, with the Ekso group improving by 34%, the BWSTT group improving by 28%, and the passive control group improving by 18%.[5]

A study of 16 individuals with incomplete tetraplegia who were randomized to complete an extensive Ekso or activities based program offered thrice per week for 24 weeks showed no difference in walking endurance between groups, though both groups improved.[6]

Some studies completed clinical outcomes within the exoskeleton, specifically those that studied participants with complete injuries or who were unable to walk without a device. One study of 10 patients who completed a 10-session ABLE exoskeleton walking program over five weeks showed similar results in the exoskeleton versus KAFOs.[7] In a crossover study, 70% of participants were able to walk >80 m in ReWalk or Ekso during a 6MWT by 12 sessions, and 82% of participants met this metric by the end of the intervention, with the average distance covered at 36 sessions being 125.3±40.4 m.[8] Those who used ReWalk tended to walk further in 6MWT, however they also had less deficits at baseline than those who used Ekso.[8]

There are many case studies that examine how endurance changes after using an exoskeleton. A statistically significant improvement in 6MWT distance was seen after 12 sessions of walking in Able for 24 subjects with SCI who were able to ambulate at baseline and post-training.[9] Small improvements of up to 10 m during the 6MWT were seen after 20 sessions of walking in ReWalk.[10] Six subjects with thoracic or lumbar AIS C injuries improved after 20 sessions of Ekso by an average of 51.5 m during 6MWT, with five of those subjects improving by 50% or more.[11]

A large number of studies measured the distance one could cover in 6 minutes in the exoskeleton. Distance ranges were from 36m to 255m with intervention length between 3 and 120 sessions in different devices including ReWalk, Uan.Go, Ekso, and Indego.[12–22] Some of these studies tracked improvements in 6MWT distance over the period of subjects learning how to utilize an exoskeleton. Improvements varied depending on exoskeleton and duration of intervention. Thirteen sessions of Uan.Go resulted in an improvement of 40 m.[13] Twenty sessions of Ekso resulted in an improvement of 12.8 m by participants who were unable to walk prior to exoskeleton treatment, 36.07 m in eight participants of which seven were motor complete, and 47 m in a sample of three subjects with lower thoracic to upper lumbar injuries, two of which were complete.[21,23,24] The same number of sessions in ReWalk resulted in an improvement of 23.2 m.[10] Midway to endpoint assessments, spanning 12 sessions, demonstrated improvements of 69.5 m in a study using Ekso and 15.5 m in a study using Indego[18,25], while another study showed that participants could walk in the Able exoskeleton 1.9 times further at session 12 versus session 1.[9] Distance walked, when stratified by injury level, was lower for those with higher injuries.[15,20] Outdoor 6MWT distances were also longer than indoor 6MWT distances, if measured within the same sample.[21,24] One study measured the 2 minute walk test and found that longest walks completed within a 24 session protocol were between 13.8 and 24.9 m, which took place between session 10 and 21.[26] When compared to KAFOs, subjects covered 73% more distance and required 3.2 times less exertion in 6 minutes in the Indego.[27]

A number of reviews comment on how endurance changes after using an exoskeleton in a population with SCI. One that examined 28 articles determined that the mean distance during a 6MWT was 108.9 m.[28] Another review concluded that to see significant change in walking performance in persons with incomplete SCI, at least 20 sessions must be prescribed.[29] Some review articles report that overground exoskeleton use results in a significant increase in distance traveled over 6 minutes[29,30], while some do not agree that there is a significant

change.[31] Two meta-analyses determined that significant change in endurance resulting from using an exoskeleton was only present in patients with a duration of injury less than six months.[31,32] When compared to KAFOs, one review reports that the few articles that look at this do not agree that one intervention is better than the other, though a greater percentage of these articles demonstrate superiority of an overground exoskeleton in the 6MWT.[33] Review articles also commented on the range of frequency and length of study protocols.[29,34]

Stroke (CVA)

Walking endurance is frequently measured in studies using participants with CVA. One randomized trial of 75 participants with subacute stroke compared five sessions per week of Ekso or conventional gait training in addition to conventional rehabilitation sessions provided over three weeks. Endurance measured through 6MWT improved for both groups, from 48.6±42.39 m to 139.24±104.7 m in the Ekso group and 44.29±59.15 m to 149.43±130.15 m in the conventional group.[35] These improvements were both significant, but not significantly different from each other.[35] This was confirmed by a similar number of people in each group who achieved the MCID.[35] Another randomized trial separated 32 subjects with chronic CVA to receive either ExoAtlet or Lokomat training provided three times a week for eight weeks after doing a standard physical therapy program. Both groups improved 6MWT, but difference between groups was similar, showing no superiority of one intervention.[36]

Forty-six participants who underwent 15±2 sessions of Ekso gait training showed that in the subgroup of the 32 subjects who were able to walk at both baseline and conclusion of the study, the distance covered during 6MWT improved from 69.53±58.46 m to 130.41±88.81 m.[37] Another study showed improvement in 6MWT distance in 12 subjects with subacute CVA after undergoing 12 sessions of Ekso gait training over 4 weeks.[38] Distance improved from 79.5±46.8 m to 92.0±59.3 m in subjects with chronic CVA and from 157.6±77.6 m to 205.1±113.2 m in subjects with subacute CVA which were both significant improvements.[38] On the contrary, a 12.6±1.95 session Ekso gait training program did not result in significant changes in the 6MWT between pre- and post-intervention in five subjects with stroke.[39]

Multiple review articles exist that comment on endurance in participants with CVA. Some revealed that using an exoskeleton had a significant positive effect on walking endurance[40–42], while others showed no significant difference between groups.[43–47]

Multiple Sclerosis (MS)

There are two known randomized controlled trials using exoskeletons in subjects with MS. In one, the effects of 4 weeks of Ekso walking were compared with those of conventional gait training when each was delivered twice weekly. The robotic group demonstrated improvement in 6MWT distance as compared to minimal changes of the control group, but it is likely that this effect was due to differences in baseline performance where the control group was more impaired.[48] The other compared the same interventions offered at the same frequency in 4 participants with relapsing-remitting MS and found that endurance improved 13% in the control group while the Ekso group showed minimal change.[49] Again this could be attributed to difference in baseline measures, this time with the Ekso group being more impaired.[49]

A case study of a 71 year old male who trained with Uan.Go ten times showed improvements in 6MWT distance from 53 m at baseline to 61 m after intervention.[50] In another study of 10 participants who used Ekso five times per week for three weeks showed no difference in 6MWT distance between pre- and post-intervention.[51]

A unique study had 10 subjects perform a 6MWT in an exoskeleton and outside of the device. Six subjects walked faster in Ekso, while the other four walked faster on their own.[52]

Two reviews examined gait training with a robotic device on subjects with MS. One reviewed 17 papers and the other 16 studies. Both showed that robotics helped improve walking endurance in participants with MS.[53,54]

Conclusion

Endurance is measured in the research both while wearing the exoskeleton and as a result of training with an exoskeleton.

Most studies agree that while wearing an exoskeleton, any user can complete a walk of at least 6 minutes, and that when this assessment is completed multiple times over the course of learning to use the device, users will improve in the amount of distance they cover. Distance walked during this time varies largely, but all are below what is considered normal for a healthy, older adult.

For persons who are able to walk independently before and after exoskeleton intervention, the majority of studies agree that endurance improves. Some report that endurance after exoskeleton training improves moreso than conventional therapy or a control group, while others report similar levels of improvement. No articles report that endurance worsens from using an exoskeleton.

Barriers to this research include the variety in number of total sessions provided as an intervention as well as the time over which the intervention takes place. The variety of exoskeleton devices used could also affect the outcomes. Finally, we don't know how these devices are being used in the research. These technologies are complicated with significant differences and many options in their software, and articles do not typically provide insight into what programs the subjects walked in and how much they were challenged during this. This choice of software could also affect the improvements made in endurance.

References

1. Louie DR, Mortenson WB, Durocher M, et al. Efficacy of an exoskeleton-based physical therapy program for non-ambulatory patients during subacute stroke rehabilitation: a randomized controlled trial. *J NeuroEngineering Rehabil*. 2021;18(1):149. doi:10.1186/s12984-021-00942-z

2. Nolan KJ, Karunakaran KK, Chervin K, et al. Robotic Exoskeleton Gait Training During Acute Stroke Inpatient Rehabilitation. *Front Neurorobot*. 2020;14:581815. doi:10.3389/fnbot.2020.581815

3. Karunakaran KK, Gute S, Ames GR, Chervin K, Dandola CM, Nolan KJ. Effect of robotic exoskeleton gait training during acute stroke on functional ambulation. *NeuroRehabilitation*. 2021;48(4):493-503. doi:10.3233/NRE-210010

4. Chang SH, Afzal T, TIRR SCI Clinical Exoskeleton Group, Berliner J, Francisco GE. Exoskeleton-assisted gait training to improve gait in individuals with spinal cord injury: a pilot randomized study. *Pilot Feasibility Stud*. 2018;4:62. doi:10.1186/s40814-018-0247-y

5. Edwards DJ, Forrest G, Cortes M, et al. Walking improvement in chronic incomplete spinal cord injury with exoskeleton robotic training (WISE): a randomized controlled trial. *Spinal Cord*. 2022;60(6):522-532. doi:10.1038/s41393-022-00751-8

6. Shackleton C, Evans R, West S, et al. Robotic locomotor training in a low-resource setting: a randomized pilot and feasibility trial. *Disability and Rehabilitation*. Published online August 22, 2023:1-10. doi:10.1080/09638288.2023.2245751

7. Rodríguez-Fernández A, Lobo-Prat J, Tarragó R, et al. Comparing walking with knee-ankle-foot orthoses and a knee-powered exoskeleton after spinal cord injury: a randomized, crossover clinical trial. *Sci Rep*. 2022;12(1):19150. doi:10.1038/s41598-022-23556-4

8. Hong E, Gorman PH, Forrest GF, et al. 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

9. Wright MA, Herzog F, Mas-Vinyals A, et al. Multicentric investigation on the safety, feasibility and usability of the ABLE lower-limb robotic exoskeleton for individuals with spinal cord injury: a framework towards the standardisation of clinical evaluations. *J Neuroeng Rehabil*. 2023;20(1):45. doi:10.1186/s12984-023-01165-0

10. Benson I, Hart K, Tussler D, Van Middendorp JJ. Lower-limb exoskeletons for individuals with chronic spinal cord injury: findings from a feasibility study. *Clin Rehabil*. 2016;30(1):73-84. doi:10.1177/0269215515575166

11. Milia P, De Salvo F, Caserio M, et al. Neurorehabilitation in paraplegic patients with an active powered exoskeleton (Ekso). *Digit Med*. 2016;2(4):163. doi:10.4103/digm.digm_51_16

12. Asselin P, Cirnigliaro CM, Kornfeld S, et al. Effect of Exoskeletal-Assisted Walking on Soft Tissue Body Composition in Persons With Spinal Cord Injury. *Arch Phys Med Rehabil*. 2021;102(2):196-202. doi:10.1016/j.apmr.2020.07.018

13. Lamberti G, Sesenna G, Paja Q, Ciardi G. Rehabilitation Program for Gait Training Using UAN.GO, a Powered Exoskeleton: A Case Report. *Neurol Int*. 2022;14(2):536-546. doi:10.3390/neurolint14020043

14. Kressler J, Domingo A. Cardiometabolic Challenges Provided by Variable Assisted Exoskeletal Versus Overground Walking in Chronic Motor-incomplete Paraplegia: A Case Series. *Journal of Neurologic Physical Therapy*. 2019;43(2):128-135. doi:10.1097/NPT.0000000000000262

15. Hartigan C, Kandilakis C, Dalley S, et al. Mobility Outcomes Following Five Training Sessions with a Powered Exoskeleton. *Top Spinal Cord Inj Rehabil*. 2015;21(2):93-99. doi:10.1310/sci2102-93

16. Guanziroli E, Cazzaniga M, Colombo L, Basilico S, Legnani G, Molteni F. Assistive powered exoskeleton for complete spinal cord injury: correlations between walking ability and exoskeleton control. *Eur J Phys Rehabil Med*. 2019;55(2):209-216. doi:10.23736/S1973-9087.18.05308-X

17. Khan AS, Livingstone DC, Hurd CL, et al. Retraining walking over ground in a powered exoskeleton after spinal cord injury: a prospective cohort study to examine functional gains and neuroplasticity. *J NeuroEngineering Rehabil*. 2019;16(1):145. doi:10.1186/s12984-019-0585-x

18. McIntosh K, Charbonneau R, Bensaada Y, Bhatiya U, Ho C. The Safety and Feasibility of Exoskeletal-Assisted Walking in Acute Rehabilitation After Spinal Cord Injury. *Archives of Physical Medicine and Rehabilitation*. 2020;101(1):113-120. doi:10.1016/j.apmr.2019.09.005

19. Yang A, Asselin P, Knezevic S, Kornfeld S, Spungen AM. Assessment of In-Hospital Walking Velocity and Level of Assistance in a Powered Exoskeleton in Persons with Spinal Cord Injury. *Top Spinal Cord Inj Rehabil*. 2015;21(2):100-109. doi:10.1310/sci2102-100

20. Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A. Safety and tolerance of the ReWalk[TM] exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study. *J Spinal Cord Med*. 2012;35(2):96-101. doi:10.1179/2045772312Y.0000000003

21. Sale P, Russo EF, Russo M, et al. Effects on mobility training and de-adaptations in subjects with Spinal Cord Injury due to a Wearable Robot: a preliminary report. *BMC Neurol*. 2016;16(1):12. doi:10.1186/s12883-016-0536-0

22. Kwon SH, Lee BS, Lee HJ, et al. Energy Efficiency and Patient Satisfaction of Gait With Knee-Ankle-Foot Orthosis and Robot (ReWalk)-Assisted Gait in Patients With Spinal Cord Injury. *Ann Rehabil Med*. 2020;44(2):131-141. doi:10.5535/arm.2020.44.2.131

23. Stampacchia G, Olivieri M, Rustici A, D'Avino C, Gerini A, Mazzoleni S. Gait rehabilitation in persons with spinal cord injury using innovative technologies: an observational study. *Spinal Cord*. 2020;58(9):988-997. doi:10.1038/s41393-020-0454-2

24. Sale P, Russo EF, Scarton A, Calabrò RS, Masiero S, Filoni S. Training for mobility with exoskeleton robot in spinal cord injury patients: a pilot study. *Eur J Phys Rehabil Med*. 2018;54(5). doi:10.23736/S1973-9087.18.04819-0

25. Tefertiller C, Hays K, Jones J, et al. 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

26. Kozlowski AJ, Bryce TN, Dijkers MP. Time and Effort Required by Persons with Spinal Cord Injury to Learn to Use a Powered Exoskeleton for Assisted Walking. *Top Spinal Cord Inj Rehabil*. 2015;21(2):110-121. doi:10.1310/sci2102-110

27. Farris RJ, Quintero HA, Murray SA, Ha KH, Hartigan C, Goldfarb M. A Preliminary Assessment of Legged Mobility Provided by a Lower Limb Exoskeleton for Persons With Paraplegia. *IEEE Trans Neural Syst Rehabil Eng*. 2014;22(3):482-490. doi:10.1109/TNSRE.2013.2268320

28. Tan K, Koyama S, Sakurai H, Teranishi T, Kanada Y, Tanabe S. Wearable robotic exoskeleton for gait reconstruction in patients with spinal cord injury: A literature review. *Journal of Orthopaedic Translation*. 2021;28:55-64. doi:10.1016/j.jot.2021.01.001

29. Stampacchia G, Gazzotti V, Olivieri M, et al. Gait robot-assisted rehabilitation in persons with spinal cord injury: A scoping review. Morone G, Riener R, Mazzoleni S, eds. *NRE*. 2022;51(4):609-647. doi:10.3233/NRE-220061

30. 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

31. Liu W, Chen J. The efficacy of exoskeleton robotic training on ambulation recovery in patients with spinal cord injury: A meta-analysis. *The Journal of Spinal Cord Medicine*. Published online August 3, 2023:1-10. doi:10.1080/10790268.2023.2214482

32. Li R, Ding M, Wang J, et al. Effectiveness of robotic-assisted gait training on cardiopulmonary fitness and exercise capacity for incomplete spinal cord injury: A systematic review and meta-analysis of randomized controlled trials. *Clin Rehabil*. 2023;37(3):312-329. doi:10.1177/02692155221133474

33. Zhang C, Li N, Xue X, Lu X, Li D, Hong Q. Effects of lower limb exoskeleton gait orthosis compared to mechanical gait orthosis on rehabilitation of patients with spinal cord injury: A systematic review and future perspectives. *Gait Posture*. 2023;102:64-71. doi:10.1016/j.gaitpost.2023.03.008

34. Nepomuceno P, Souza WH, Pakosh M, Musselman KE, Craven BC. Exoskeleton-based exercises for overground gait and balance rehabilitation in spinal cord injury: a systematic review of dose and dosage parameters. *J Neuroeng Rehabil*. 2024;21(1):73. doi:10.1186/s12984-024-01365-2

35. Molteni F, Guanziroli E, Goffredo M, et al. Gait Recovery with an Overground Powered Exoskeleton: A Randomized Controlled Trial on Subacute Stroke Subjects. *Brain Sciences*. 2021;11(1):104. doi:10.3390/brainsci11010104

36. Elmas Bodur B, Erdoğanoğlu Y, Asena Sel S. Effects of robotic-assisted gait training on physical capacity, and quality of life among chronic stroke patients: A randomized controlled study. *Journal of Clinical Neuroscience*. 2024;120:129-137. doi:10.1016/j.jocn.2024.01.010

37. Goffredo M, Guanziroli E, Pournajaf S, et al. Overground wearable powered exoskeleton for gait training in subacute stroke subjects: clinical and gait assessments. *Eur J Phys Rehabil Med*. 2020;55(6). doi:10.23736/S1973-9087.19.05574-6

38. Molteni F, Gasperini G, Gaffuri M, et al. Wearable robotic exoskeleton for overground gait training in sub-acute and chronic hemiparetic stroke patients: preliminary results. *Eur J Phys Rehabil Med*. 2017;53(5). doi:10.23736/S1973-9087.17.04591-9

39. Zhu F, Kern M, Fowkes E, et al. Effects of an exoskeleton-assisted gait training on post-stroke lower-limb muscle coordination. *J Neural Eng*. 2021;18(4). doi:10.1088/1741-2552/abf0d5

40. Hsu TH, Tsai CL, Chi JY, Hsu CY, Lin YN. Effect of wearable exoskeleton on post-stroke gait: A systematic review and meta-analysis. *Annals of Physical and Rehabilitation Medicine*. 2023;66(1):101674. doi:10.1016/j.rehab.2022.101674

41. Yang J, Gong Y, Yu L, Peng L, Cui Y, Huang H. Effect of exoskeleton robot-assisted training on gait function in chronic stroke survivors: a systematic review of randomised controlled trials. *BMJ Open*. 2023;13(9):e074481. doi:10.1136/bmjopen-2023-074481

42. Yamamoto R, Sasaki S, Kuwahara W, Kawakami M, Kaneko F. Effect of exoskeleton-assisted Body Weight-Supported Treadmill Training on gait function for patients with chronic stroke: a scoping review. *J Neuroeng Rehabil*. 2022;19(1):143. doi:10.1186/s12984-022-01111-6

43. Leow XRG, Ng SLA, Lau Y. Overground Robotic Exoskeleton Training for Patients With Stroke on Walking-Related Outcomes: A Systematic Review and Meta-analysis of Randomized Controlled Trials. *Archives of Physical Medicine and Rehabilitation*. 2023;104(10):1698-1710. doi:10.1016/j.apmr.2023.03.006

44. 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(9S2). doi:10.1016/j.pmrj.2018.06.005

45. Moucheboeuf G, Griffier R, Gasq D, et al. Effects of robotic gait training after stroke: A meta-analysis. *Ann Phys Rehabil Med*. 2020;63(6):518-534. doi:10.1016/j.rehab.2020.02.008

46. Mehrholz J, Pohl M. Electromechanical-assisted gait training after stroke: a systematic review comparing end-effector and exoskeleton devices. *J Rehabil Med*. 2012;44(3):193-199. doi:10.2340/16501977-0943

47. Yang J, Zhu Y, Li H, Wang K, Li D, Qi Q. Effect of robotic exoskeleton training on lower limb function, activity and participation in stroke patients: a systematic review and meta-analysis of randomized controlled trials. *Front Neurol*. 2024;15:1453781. doi:10.3389/fneur.2024.1453781

48. Androwis GJ, Sandroff BM, Niewrzol P, et al. A pilot randomized controlled trial of robotic exoskeleton-assisted exercise rehabilitation in multiple sclerosis. *Mult Scler Relat Disord*. 2021;51:102936. doi:10.1016/j.msard.2021.102936

49. Androwis GJ, Kwasnica MA, Niewrzol P, et al. Mobility and Cognitive Improvements Resulted from Overground Robotic Exoskeleton Gait-Training in Persons with MS. In: *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE; 2019:4454-4457. doi:10.1109/EMBC.2019.8857029

50. Sesenna G, Calzolari C, Gruppi MP, Ciardi G. Walking with UAN.GO Exoskeleton: Training and Compliance in a Multiple Sclerosis Patient. *Neurol Int*. 2021;13(3):428-438. doi:10.3390/neurolint13030042

51. Afzal T, Tseng SC, Lincoln JA, Kern M, Francisco GE, Chang SH. Exoskeleton-assisted Gait Training in Persons With Multiple Sclerosis: A Single-Group Pilot Study. *Arch Phys Med Rehabil*. 2020;101(4):599-606. doi:10.1016/j.apmr.2019.10.192

52. Afzal T, Zhu F, Tseng SC, et al. Evaluation of Muscle Synergy During Exoskeleton-Assisted Walking in Persons With Multiple Sclerosis. *IEEE Trans Biomed Eng*. 2022;69(10):3265-3274. doi:10.1109/TBME.2022.3166705

53. Yang FA, Lin CL, Huang WC, Wang HY, Peng CW, Chen HC. Effect of Robot-Assisted Gait Training on Multiple Sclerosis: A Systematic Review and Meta-analysis of Randomized Controlled Trials. *Neurorehabil Neural Repair*. 2023;37(4):228-239. doi:10.1177/15459683231167850

54. Calabrò RS, Cassio A, Mazzoli D, et al. What does evidence tell us about the use of gait robotic devices in patients with multiple sclerosis? A comprehensive systematic review on functional outcomes and clinical recommendations. *Eur J Phys Rehabil Med*. 2021;57(5):841-849. doi:10.23736/S1973-9087.21.06915-X

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Effect of robotic exoskeleton training on lower limb function, activity and participation in stroke patients: a systematic review and meta-analysis of randomized controlled trials	Yang J, Zhu Y, Li H, Wang K, Li D, Qi Q	Front Neurol. 2024 Aug 13:15:1453781	Multiple – Review Article	CVA
Robotic locomotor training in a low-resource setting: a randomized pilot and feasibility trial	Shackleton C, Evans R, West S, Bantjes J, Swartz L, Derman W, Albertus Y	Disabil Rehabil. 2024 Jul;46(15):3363-3372	Ekso	SCI
Exoskeleton-based exercises for overground gait and balance rehabilitation in spinal cord injury: a systematic review of dose and dosage parameters	Nepomuceno P, Souza WH, Pakosh M, Musselman KE, Craven BC	J Neuroeng Rehabil. 2024 May 5;21(1):73	Multiple – Review Article	SCI
Effects of robotic-assisted gait training on physical capacity, and quality of life among chronic stroke patients: A randomized controlled study	Bodur BE, Erdoğanoğlu Y, Sel SA	J Clin Neurosci. 2024 Feb:120:129-137	ExoAtlet	CVA
Overground robotic exoskeleton training for patients with stroke on walking-related outcomes: A systematic review and meta-analysis of randomised controlled trials	Leow XRG, Ng SLA, Lau Y	Arch Phys Med Rehabil. 2023 Oct;104(10):1698-1710.	Multiple – Review Article	CVA
Effect of exoskeleton robot-assisted training on gait function in chronic stroke survivors: a systematic review of randomised controlled trials	Yang J, Gong Y, Yu L, Peng L, Cui Y, Huang H	BMJ Open. 2023 Sep 14;13(9):e074481	Multiple – Review Article	CVA
The efficacy of exoskeleton robotic training on ambulation recovery in patients with spinal cord injury: A meta-analysis	Liu W, Chen J	J Spinal Cord Med. 2023 Aug 3:1-10	Multiple – Review Article	SCI
Effects of lower limb exoskeleton gait orthosis compared to mechanical gait orthosis on rehabilitation of patients with spinal cord injury: A systematic review and future perspectives	Zhang C, Li N, Xue X, Lu X, Li D, Hong Q	Gait Posture. 2023 May:102:64-71	Multiple – Review Article	SCI
Effect of Robot-Assisted Gait Training on Multiple Sclerosis: A Systematic Review and Meta-analysis of Randomized Controlled Trials.	Yang FA, Lin CL, Huang WC, Wang HY, Peng CW, Chen HC.	Neurorehabil Neural Repair. 2023 Apr;37(4):228-239	Multiple – Review Article	MS

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Multicentric investigation on the safety, feasibility and usability of the ABLE lower-limb robotic exoskeleton for individuals with spinal cord injury: a framework towards the standardisation of clinical evaluations	Wright MA, Herzog F, Mas-Vinyals A, et al.	J Neuroeng Rehabil. 2023 Apr 12;20(1):45	Able	SCI
Effectiveness of robotic-assisted gait training on cardiopulmonary fitness and exercise capacity for incomplete spinal cord injury: A systematic review and meta-analysis of randomized controlled trials	Li R, Ding M, Wang J, Pan H, Sun X, Huang L, Fu C, He C, Wei Q	Clin Rehabil. 2023 Mar;37(3):312-329	Multiple – Review Article	SCI
Effect of wearable exoskeleton on post-stroke gait: A systematic review and meta-analysis	Hsu TH, Tsai CL, Chi JY, Hsu CY, Lin YN.	Ann Phys Rehabil Med. 2023 Feb;66(1):101674	Multiple – Review Article	CVA
The efficacy of gait rehabilitations for the treatment of incomplete spinal cord injury: a systematic review and network meta-analysis	Patathong T, Klaewkasikum K, Woratanarat P, Rattanasiri S, Anothaisintawee T, Woratanarat T, Thakkinstian A	J Orthop Surg Res. 2023 Jan 23;18(1):60	Ekso	SCI
Effect of exoskeleton-assisted Body Weight-Supported Treadmill Training on gait function for patients with chronic stroke a scoping review	Yamamoto R, Sasaki S, Kuwahara W, Kawakami M, Kaneko F	J Neuroeng Rehabil. 2022 Dec 21;19(1):143	Multiple – Review Article	CVA
Comparing walking with knee-ankle-foot orthoses and a knee-powered exoskeleton after spinal cord injury: a randomized, crossover clinical trial	Rodríguez-Fernández A, Lobo-Prat J, Tarragó R, et al.	Sci Rep. 2022 Nov 9;12(1):19150	Able	SCI
Evaluation of Muscle Synergy During Exoskeleton-Assisted Walking in Persons With Multiple Sclerosis	Afzal T, Zhu F, Tseng SC, Lincoln JA, Francisco GE, Su H, Chang SH	IEEE Trans Biomed Eng. 2022 Oct;69(10):3265-3274	Ekso	MS
Wearable powered exoskeletons for gait training in tetraplegia: a systematic review on feasibility, safety and potential health benefits	Tapia GR, Doumas I, Lejeune T, Previnaire JG	Acta Neurol Belg. 2022 Oct;122(5):1149-1162	Multiple – Review Article	SCI
Rehabilitation Program for Gait Training Using UAN.GO, a Powered Exoskeleton: A Case Report	Lamberti G, Sesenna G, Paja Q, Ciardi G.	2022 Jun 16;14(2):536-546	Uan.Go	SCI

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Walking improvement in chronic incomplete spinal cord injury with exoskeleton robotic training (WISE): a randomized controlled trial	Edwards DJ, Forrest G, Cortes M, Weightman MM, Sadowsky C, Chang SH, Furman K, Bialek A, Prokup S, Carlow J, VanHiel L, Kemp L, Musick D, Campo M, Jayaraman A	Spinal Cord. 2022 Jun;60(6):522-532	Ekso	SCI
Comparison of Efficacy of Lokomat and Wearable Exoskeleton-Assisted Gait Training in People With Spinal Cord Injury: A Systematic Review and Network Meta-Analysis.	Zhang L, Lin F, Sun L, Chen C.	Front Neurol. 2022 Apr 13:13:772660	Multiple – Review Article	SCI
Gait robot-assisted rehabilitation in persons with spinal cord injury: A scoping review	Stampacchia G, Gazzotti V, Olivieri M, Andrenelli E, Bonaiuti D, Calabro RS, Carmignano SM, Cassio A, Fundaro C, Companini I, Mazzoli D, Cerulli S, Chisari C, Colombo V, Dalise S, Mazzoleni D, Melegari C, Merlo A, Boldrini P, Mazzoleni S, Posteraro F, Mazzucchelli M, Benanti P, Castelli E, Draicchio F, Falabella V, Galeri S, Gimigliano F, Grigioni M, Mazzon S, Molteni F, Morone G, Petrarca M, Picelli A, Senatore M, Turchetti G, Bizzarrini E	NeuroRehabilitation. 2022;51(4):609-647	Multiple – Review Article	SCI
Robotic Exoskeleton Gait Training in Stroke: An Electromyography-Based Evaluation	Longatelli V, Pedrocchi A, Guanziroli E, Molteni F, Gandolla M	Front Neurorobot. 2021 Nov 26:15:733738	Ekso	CVA

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
What does evidence tell us about the use of gait robotic devices in patients with multiple sclerosis? A comprehensive systematic review on functional outcomes and clinical recommendations	Calabro RS, Cassio A, Mazzoli D, Andrenelli E, Bizzarini E, Capaninin I, Carmignano SM, Cerruli S, Chisari C, Colombo V, Dalise S, Fundaro C, Gazzotti V, Mazzoleni D, Mazzucchelli M, Melegari C, Merlo A, Stampacchia G, Boldrini P, Mazzoleni S, Posteraro F, Benati P, Castelli E, Draicchio F, Falabella V, Galeri S, Gimigliano F, Grigioni M, Mazzon S, Molteni F, Petrarca M, Picelli A, Senatore M, Turchetti G, Morone G, Bonaiuti D	Eur J Phys Rehabil Med. 2021 Oct;57(5):841-849	Multiple – Review Article	MS
Efficacy of an exoskeleton-based physical therapy program for non-ambulatory patients during subacute stroke rehabilitation: a randomized controlled trial	Louie DR, Mortenson WB, Durocher M, Schneeberg A, Teasell R, Yao J, Eng JJ	J Neuroeng Rehabil. 2021 Oct 10;18(1):149	Ekso	CVA
Walking with UAN.GO Exoskeleton: Training and Compliance in a Multiple Sclerosis Patient	Sesenna G, Calzolari C, Gruppi MP, Ciardi G.	Neurol Int. 2021 Aug 23;13(3):428-438	Uan.Go	MS
Outcomes of a Multicenter Safety and Efficacy Study of the SuitX Phoenix Powered Exoskeleton for Ambulation by Patients with Spinal Cord Injury	Koljonen PA, Virk AS, Jeong Y, McKinley M, Latorre J, Caballero A, Hu Y, Wong YW, Cheung K, Kazerooni H	Front Neurol. 2021 Jul 19:12:689751	SuitX	SCI
Effects of an exoskeleton-assisted gait training on post-stroke lower-limb muscle coordination	Zhu F, Kern M, Fowkes E, Afzal T, Contreras-Vidal JL, Francisco GE, Chang SH	J Neural Eng. 2021 Jun 4;18(4)	Ekso	CVA
A pilot randomized controlled trial of robotic exoskeleton-assisted exercise rehabilitation in multiple sclerosis	Androwis GJ, Sandroff BM, Niewrzol P, Wylie GR, Yue G, DeLuca J	Mult Scler Relat Disord. 2021 Jun:51:102936	Ekso	MS
Wearable robotic exoskeleton for gait reconstruction in patients with spinal cord injury: A literature review	Tan K, Koyama S, Sakurai H, Teranishi T, Kanada Y, Tanabe S	J Orthop Translat . 2021 Mar 1:28:55-64	Multiple – Review Article	SCI
Effect of Exoskeletal-Assisted Walking on Soft Tissue Body Composition in Persons with Spinal Cord Injury	Asselin P, Cirnigliaro CM, Kornfeld S, Knezevic S, Lackow R, Elliott M, Bauman WA, Spungen AM	Arch Phys Med Rehabil. 2021 Feb;102(2):196-202	ReWalk	SCI

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Effect of robotic exoskeleton gait training during acute stroke on functional ambulation	Karunakaran KK, Gute S, Ames GR, Chervin K, Dandola CM, Nolan KJ	NeuroRehabilitation. 2021;48(4):493-503	Ekso	CVA
Gait Recovery with an Overground Powered Exoskeleton: A Randomized Controlled Trial on Subacute Stroke Subjects	Molteni F, Guanziroli E, Goffredo M, Calabrò RS, Pournajaf S, Gaffuri M, Gasperini G, Filoni S, Baratta S, Galafate D, Le Pera D, Bramanti P, Franceschini M	Brain Sci. 2021 Jan 14;11(1):104	Ekso	CVA
Effects of robotic gait training after stroke: A meta-analysis	Moucheboeuf G, Griffier R, Gasq D, et al.	Ann Phys Rehabil Med. 2020 Nov;63(6):518-534.	Multiple – Review Article	CVA
Robotic Exoskeleton Gait Training During Acute Stroke Inpatient Rehabilitation	Nolan KJ, Karunakaran KK, Chervin K, Monfett MR, Bapineedu RK, Jasey NN, Oh-Park M	Front Neurorobot. 2020 Oct 30:14:581815	Ekso	CVA
Gait rehabilitation in persons with spinal cord injury using innovative technologies: an observational study	Stampacchia G, Olivieri M, Rustici A, D'Avino C, Gerini A, Mazzoleni S	Spinal Cord. 2020 Sep;58(9):988-997	Ekso	SCI
Mobility Skills With Exoskeletal-Assisted Walking in Persons With SCI Results From a Three Center Randomized Clinical Trial	Hong EK, Gorman PH, Forrest GF, Asselin PK, Knezevic S, Scott W, Wojciehowski SB, Kornfeld S, Spungen AM	Front Robot AI. 2020 Aug 4:7:93	ReWalk, Ekso	SCI
Exoskeleton-assisted Gait Training in Persons With Multiple Sclerosis: A Single-Group Pilot Study	Afzal T, Tseng SC, Lincoln JA, Kern M, Francisco GE, Chang SH	Arch Phys Med Rehabil. 2020 Apr;101(4):599-606	Ekso	MS
Energy Efficiency and Patient Satisfaction of Gait With Knee-Ankle-Foot Orthosis and Robot (ReWalk)-Assisted Gait in Patients With Spinal Cord Injury	Kwon SH, Lee BS, Lee HJ, et al.	Ann Rehabil Med. 2020 Apr;44(2):131-141	ReWalk	SCI
The Safety and Feasibility of Exoskeletal-Assisted Walking in Acute Rehabilitation After Spinal Cord Injury	McIntosh K, Charbonneau R, Bensaada Y, Bhatiya U, Ho C.	Arch Phys Med Rehabil. 2020 Jan;101(1):113-120	Ekso	SCI

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Overground wearable powered exoskeleton for gait training in subacute stroke subjects: clinical and gait assessments.	Goffredo M, Guanziroli E, Pournajaf S, Gaffuri M, Gasperini G, Filoni S, Baratta S, Damiani C, Franceschini M, Molteni F	Eur J Phys Rehabil Med. 2019 Dec;55(6):710-721	Ekso	CVA
Retraining walking over ground in a powered exoskeleton after spinal cord injury: a prospective cohort study to examine functional gains and neuroplasticity	Khan AS, Livingstone DC, Hurd CL, Duchcherer J, Misiaszek JE, Gorassini MA, Manns PJ, Yang JF	J Neuroeng Rehabil. 2019 Nov 21;16(1):145	ReWalk	SCI
Mobility and Cognitive Improvements Resulted from Overground Robotic Exoskeleton Gait-Training in Persons with MS.	Androwis GJ, Kwasnica MA, Niewrzol P, Popok P, Fakhoury FN, Sandroff BM, Yue GH, DeLuca J	Annu Int Conf IEEE Eng Med Biol Soc. 2019 Jul:2019:4454-4457	Ekso	MS
Cardiometabolic Challenges Provided by Variable Assisted Exoskeletal Versus Overground Walking in Chronic Motor-incomplete Paraplegia: A Case Series.	Kressler J, Domingo A	J Neurol Phys Ther. 2019 Apr;43(2):128-135	Ekso	SCI
Assistive powered exoskeleton for complete spinal cord injury: correlations between walking ability and exoskeleton control	Guanziroli E, Cazzaniga M, Colombo L, Basilico S, Legnani G and Molteni F	Eur J Phys Rehabil Med. 2019 Apr;55(2):209-216	ReWalk	SCI
Initial Outcomes from a Multicenter Study Utilizing the Indego Powered Exoskeleton in Spinal Cord Injury	Tefertiller C, Hays K, Jones J, Jayaraman A, Hartigan C, Bushnik T and Forrest G	Top Spinal Cord Inj Rehabil. 2018 Winter;24(1):78-85	Indego	SCI
Training for mobility with exoskeleton robot in person with Spinal Cord Injury: a pilot study.	Sale P, Russo EF, Scarton A, Calabrò RS, Masiero S, Filoni S	Eur J Phys Rehabil Med. 2018 Oct;54(5):745-751	Ekso	SCI
Narrative Review of Exoskeleton and End-Effector Robots	Molteni F, Gasperini G, Cannaviello G, Guanziroli E	PM R. 2018 Sep;10(9 Suppl 2):S174-S188	Multiple – Review Article	CVA, SCI
Exoskeleton-assisted gait training to improve gait in individuals with spinal cord injury: a pilot randomized study	Chang SH, Afzal T, Berliner J, Francisco GE.	Pilot Feasibility Stud. 2018 Mar 5:4:62	Ekso	SCI

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Wearable robotic exoskeleton for over-ground gait training in sub-acute and chronic hemiparetic stroke patients: preliminary results	Molteni F, Gasperini G, Gaffuri M, Colombo M, Giovanzana C, Lorenzon C, Farina N, Cannaviello G, Scarano S, Proserpio D, Liberali D, Guanziroli E.	Eur J Phys Rehabil Med. 2017 Oct;53(5):676-684	Ekso	CVA
Feasibility and Safety of a Powered Exoskeleton for Assisted Walking for Persons With Multiple Sclerosis: A Single-Group Preliminary Study	Kozlowski AJ, Fabian M, Lad D, Delgado AD.	Arch Phys Med Rehabil. 2017 Jul;98(7):1300-1307	ReWalk	MS
An integrated gait rehabilitation training based on Functional Electrical Stimulation cycling and overground robotic exoskeleton in complete spinal cord injury patients: preliminary results	Mazzoleni S, Battini E, Rustici A, Stampacchia G.	IEEE Int Conf Rehabil Robot. 2017 Jul:2017:289-293	Ekso	SCI
Electromechanical assisted training for walking after stroke a major update of the evidence	Mehrholz J, Thomas S, Werner C, Kugler J, Pohl M, Elsner B	Stroke. 2017 Jun 16:STROKEAHA.117.018018	Multiple – Review Article	CVA
Accelerometry-enabled measurement of walking performance with a robotic exoskeleton: a pilot study	Lonini L, Shawen N, Scanlan K, Rymer WZ, Kording KP, Jayaraman A.	J Neuroeng Rehabil. 2016 Mar 31:13:35	ReWalk	SCI
Lower limb exoskeletons for individuals with chronic spinal cord injury: Findings from a feasibility study	Benson I, Hart K, van Middendorp JJ, Tussler D	Clin Rehabil. 2016 Jan;30(1):73-84	ABLE	SCI
Effects on mobility training and de-adaptations in subjects with Spinal Cord Injury due to a Wearable Robot: a preliminary report.	Sale P, Russo EF, Russo M, Masiero S, Piccione F, Calabrò RS, Filoni S	BMC Neurol. 2016 Jan 28:16:12	Ekso	SCI
Mobility Outcomes Following Five Training Sessions with a Powered Exoskeleton	Hartigan C, Kandilakis C, Dalley S, Clausen M, Wilson E, Morrison S, Etheridge S, and Farris R.	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):93-9	Indego	SCI
Assessment of In-Hospital Walking Velocity and Level of Assistance in a Powered Exoskeleton in Persons with Spinal Cord Injury	Yang A, Asselin P, Knezevic S, Kornfeld S, Spungen AM	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):100-9	ReWalk	SCI

All known articles assessing endurance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Time and Effort Required by Persons with Spinal Cord Injury to Learn to Use a Powered Exoskeleton for Assisted Walking.	Kozlowski A, Bryce TN, Dijkers MP	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):110-21	Ekso	SCI
Neurorehabilitation in paraplegic patients with an active powered exoskeleton (Ekso)	"Milia P, De Salvo F, Caserio M, Cope T, Weber P, Santella C, Fiorini S, Baldoni G, Bruschi R, Bigazzi B, Cencetti S, Da Campo M, Bigazzi P, Bigazzi M	NeuroRehabilitation. 2015;37(3):321-40	Ekso	SCI
A preliminary assessment of legged mobility provided by a lower limb exoskeleton for persons with paraplegia	Farris RJ, Quintero HA, Murray SA, Ha KH, Hartigan C, and Goldfarb M	IEEE Trans Neural Syst Rehabil Eng. 2014 May;22(3):482-90	Indego	SCI
Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study.	Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A.	J Spinal Cord Med. 2012 Mar;35(2):96-101	ReWalk	SCI

ABI = acquired brain injury, CVA = stroke, MS = multiple sclerosis, SCI = spinal cord injury