Balance

There are a number of articles that assess balance in participants using exoskeletons. The majority of these articles looked at a population with spinal cord injury (SCI) (28 articles) or stroke (CVA) (18 articles). These publications are a majority case series (26 articles), controlled trials (16 articles), and review articles (15 articles). Most articles assessed balance using the Timed Up and Go test (TUG) (41 articles) and/or Berg Balance Scale (Berg) (18 articles). Review articles examined studies utilizing many exoskeleton devices. Most other studies utilized the Ekso1.1/GT/NR device, referred to as "Ekso" in this paper (36 articles).

Stroke (CVA)

There are a number of randomized controlled trials that assess balance changes as a result of using an exoskeleton in the CVA population. Some show that exoskeletons are superior to conventional training in terms of improving balance[1–3], while others show equal results between groups[4–6]. One study that showed that exoskeleton training was superior to conventional gait training was a trial that randomized 40 subjects with strokes occurring at least 6 months ago who received walking therapy conventionally or with Ekso five times a week for eight weeks. The robotic group showed greater changes in TUG than the group receiving conventional gait training.[1] When data from this study was analyzed a different way, all Ekso participants achieved the Minimal Clinically Important Difference (MCID) and the Minimal Detectable Change (MDC) for the TUG, while the conventionally trained group only met the MDC.[2] A slightly lower dose of therapy 3 times a week over 8 weeks of either Ekso or conventional training resulted in statistically significant improvement in TUG time for both groups, with slight superiority of Ekso.[3] On the contrary, another study randomized 44 subjects with ischemic stroke that occurred in the last 4-12 months into receiving daily rehabilitation plus either Ekso or conventional gait training. The dosage provided for both groups was 105 minutes per day, of which 45 minutes were either Ekso or conventional gait training five days per week for four weeks. Balance was measured using a baroresistive platform and it was determined that both groups significantly improved their balance, but neither group outperformed the other in the magnitude of this improvement.[4] Another study that showed similar results between the exoskeleton and control groups utilized 17 subjects with subacute stroke and randomized them to receive 12 sessions of either ExoAtlet or conventional gait training. Berg improved significantly in both groups, while the TUG only improved in the ExoAtlet group, though the between group comparison of the change in each measure was not statistically different for either outcome measure.[5] One study that was completed in the context of inpatient rehabilitation showed significant improvements in Berg scores, but no between group differences.[6]

While they didn't have a control group, other studies compared pre-exoskeleton outcomes to outcomes completed post-exoskeleton intervention. One such study enrolled 19 subjects with chronic stroke and had them walk in Ekso 3 times per week over 4 weeks in addition to 100 minutes per weekday of verticalization. This intervention did result in improvement of -10.32 ± 14.59 seconds in the TUG.[7] Another study that showed improvement in TUG after using Ekso in a group of 46 subjects post stroke demonstrated both a greater number of people who could complete the TUG test post intervention and an improvement in test time.[8] These subjects ambulated in Ekso a total of 12-20 sessions offered 3 to 5 times per week. Fifteen subjects were unable to complete the TUG at baseline and regained the ability to complete the test post-intervention.[8] For the 7 participants who could complete the test at both time points, their time improved from 38.71 to 30.00 seconds.[8] A third study showing positive improvements in the TUG had 14 participants in a rehabilitation setting receiving both standard of care and Ekso therapy during their length of stay. At baseline, all subjects took greater than 30 seconds to complete the TUG and by the end of the study, 12 of the 14 improved their TUG time significantly.[9] A smaller study showed similar improvements in TUG in 2 individuals with acute stroke who ambulated in Ekso 3 times per week over 10 weeks. One subject improved TUG from 10 to 7.82 seconds, and the other improved from 11.46 to 9.45 seconds.[10] A different study of 14 individuals had subjects participate in an intensive program of technology assisted training which included multiple devices. Berg scores improved from 32 to 39, which was statistically significant after 28 to 82 sessions of technology assisted training.[11] While all pre-post studies discussed above showed positive results of an exoskeleton-based intervention on balance, one study did not show significant changes in TUG time in 5 subjects after 15 sessions of Ekso.[12]

There are seven known review articles that comment on exoskeletons and their effect on balance in persons with stroke. Three of them examined randomized controlled trials and showed that exoskeletons were superior to control groups providing conventional therapy for improving balance.[13–15] Another review, however, reported that exoskeleton walking demonstrated no further improvement on balance than conventional therapy.[16] Another review attempted to determine the best combination of treatment methods to improve balance measured by Berg and found that a combination of robotic training, body weight supported training, and conventional physical therapy was best.[17] A final review also looked at combinations of treatments including those that are robot assisted and virtual reality based. It found that a combination of these is best for improving Berg (82%) and TUG (93.3%).[18]

Spinal Cord Injury (SCI)

While none use balance measures as primary outcomes, there are a few studies that use subjects with SCI and assess changes in balance as compared to another intervention. Most compared Ekso training to conventional gait training. One study of 7 participants with chronic motor incomplete SCI randomized them to receive their selected gait training five times a week for 3 weeks. Both groups improved in TUG time, with the exoskeleton group having a greater percent change, but the control group having a statistically significant change.[19] It is important to note that in this study, the two groups were different at baseline, which may have skewed the results.[19] Another study that compared Ekso, conventional training, and body weight supported treadmill training found no statistically significant difference in improvement of TUG time, which improved by 18.7%, 12.7%, and 19.9% respectively.[20] One study utilized Functional Electrical Stimulation (FES) in conjunction with Ekso walking and found that balance measured by Berg improved more during the intervention period than control period in a crossover study of 6 persons with acute SCI.[21]

Single group studies examined changes in balance outcomes completed before and after exoskeleton intervention. A unique study of 8 participants with chronic motor complete SCI who averaged 30 sessions walking in the ReWalk compared the seated balance of these participants with 7 able-bodied controls using computerized posturography. The majority of participants had improvement in their seated balance after exoskeleton intervention with significant increases in ability to move center of pressure further in all directions.[22] A similar study showed improvement in limits of stability in sitting as well as improvements in sway speed in sitting with eyes closed.[23] Other studies showed improvements from pre- to post-exoskeleton intervention in the Berg and the TUG in a number of exoskeletons including ExoAtlet, Ekso, Indego, and Able and with different durations of interventions ranging from a total of 12-24 sessions.[24–28]

A number of studies examined TUG completed in an exoskeleton.[28–38] Some of these studies had the purpose of testing controls of the exoskeleton, and therefore the TUG was chosen as it involved the user transitioning from sit to stand, walking, and returning to sit. Another study modified the Berg to assess it in an exoskeleton, understanding that certain items including standing on one leg, tandem stance, and picking up an item from the ground are not possible in an exoskeleton.[39] For studies that completed testing in an exoskeleton over multiple time periods, improvements in balance were seen overtime.[35,36,38,39] A combination treatment of 20 sessions each of Ekso walking and FES cycling produced statistically significant improvements in TUG.[33]

A number of reviews using subjects with SCI comment on balance recovery after using an exoskeleton, but only one known article has this outcome as a primary goal of completing the review. In this article, 19 papers were selected. Eleven of 13 studies that examined functional restoration reported statistically significant improvements or improvements greater than MCID for gait and balance measures.[40] A metanalysis which looked at a variety of outcome measures showed that persons with SCI who received wearable exoskeleton gait training improved TUG times based on 5 studies with 93 participants.[41] Another meta-analysis showed similar results with the Berg, showing that exoskeleton training was more effective in improving balance compared to conventional gait training.[42] A final review aimed to compare the effects of exoskeleton training on persons with different SCI levels and severity. In persons with incomplete SCI who received 20 sessions, TUG improved, while no improvement was seen in those trained in a body weight supported treadmill based robotic device.[43]

Multiple Sclerosis (MS)

There are a number of studies and one review all examining the effect that walking in an exoskeleton has on balance in persons with MS. Most assess balance using the TUG. One randomized controlled trial compared 4 weeks of Ekso walking with 4 weeks of conventional therapy delivered twice weekly. While not statistically significant, the robotic group demonstrated substantial improvements (from 19.3 seconds to 14.3 seconds) while the conventional therapy group demonstrated minimal worsening (from 22.4 seconds to 22.8 seconds).[44] Another randomized trial utilized 36 participants who required an assistive device for outdoor walking and all received weekly, 1 hour conventional PT sessions. In addition, the intervention group also received twice weekly Ekso sessions for a duration of 3 months. The group that received Ekso training improved on their TUG time from 22.86±12.04 to 20.61±10.37 seconds, while the control group worsened by an average of 1.35 seconds.[45] It was also important to note that this improvement did not increase fatigue perception, which is important in persons with this diagnosis.[45] A smaller study randomized a group of 4 equally to either receive 8 sessions of Ekso or conventional gait training. The group who walked in Ekso improved by 26% while the control group only improved by 1% on the TUG.[46] In a retrospective study, 20 patients were divided into two groups, one who received gait training with Ekso and the other through conventional methods for a total of 40 sessions. Both groups improved significantly on the Berg, but only the Ekso group demonstrated a significant improvement in TUG.[47]

In a unique study that used force plates to determine postural balance and center of pressure displacements, 14 subjects walked in Ekso 15 times over 3 weeks. By this method of measurement, no significant difference were seen between assessment time periods.[48]

One study demonstrated no significant improvement in balance due to walking in an exoskeleton. This case series had 10 subjects walking in Ekso for 15 sessions over 3 weeks. While improvement from 33.4±12.2 to 28.6±13.7 seconds was seen, this improvement was only approaching significance with a p value of 0.1.[49] This study only recruited subjects with an EDSS from 5 – 6.5 (ambulates without aid or rest for 200m to constant bilateral UE assist walking for 20m without rest), whereas a case study of one woman with an EDSS of 8 (restricted to bed or chair) also showed no improvement in balance measured by the Berg after 15 sessions of Ekso walking provided twice per week.[50] Her score was a 4 at both baseline and conclusion of the study.[50] These EDSS scores do not differ significantly from participants recruited in studies above where significant improvements in balance could be seen.

One review focusing on participants with MS who used wearable or grounded exoskeletons showed that intervention groups exhibited significant improvement in balance when it was measured as a secondary outcome.[51]

Acquired Brain Injury

Only one article exists that looks at balance in a person with a brain injury. This case study examined a 22 year old male who was 2 years post traumatic injury. He walked in Ekso three times a week for four weeks. While the primary purpose of this article was to measure cortical activation, clinical measures including the TUG were completed and an improvement from 17.97 seconds to 14.69 seconds was seen.[52]

Review Articles

One article examined use of a variety of devices including exoskeletons on aging adults who were 65 and above and found that use of these devices, particularly with persons who have a neurological diagnosis, can improve balance as measured by Berg and TUG.[53]

Conclusion

While there is heterogeneity in this research in terms of device used, frequency and duration of intervention, subject diagnosis, and outcome assessing balance, most of the literature suggests that using an exoskeleton can improve balance in adults with neurological conditions. When tested in the exoskeleton, the literature agrees that with further practice in the device, balance outcomes improve. Limitations of the literature on this topic include that balance is not frequently a primary outcome measure, and that TUG is sometimes used as a measure of function versus balance. Like other research on exoskeletons, there is extreme variety in dosage and what is completed in a research setting is likely not transferable to a clinical setting.

References

1. Naro A, Pignolo L, Calabrò RS. Brain Network Organization Following Post-Stroke Neurorehabilitation. *Int J Neur Syst*. 2022;32(04):2250009. doi:10.1142/S0129065722500095

2. Calabrò RS, Naro A, Russo M, et al. Shaping neuroplasticity by using powered exoskeletons in patients with stroke: a randomized clinical trial. *J NeuroEngineering Rehabil*. 2018;15(1):35. doi:10.1186/s12984-018-0377-8

3. De Luca R, Maresca G, Balletta T, et al. Does overground robotic gait training improve non-motor outcomes in patients with chronic stroke? Findings from a pilot study. *Journal of Clinical Neuroscience*. 2020;81:240-245. doi:10.1016/j.jocn.2020.09.070

4. Rojek A, Mika A, Oleksy Ł, Stolarczyk A, Kielnar R. Effects of Exoskeleton Gait Training on Balance, Load Distribution, and Functional Status in Stroke: A Randomized Controlled Trial. *Front Neurol*. 2020;10:1344. doi:10.3389/fneur.2019.01344

5. Yoo HJ, Bae CR, Jeong H, Ko MH, Kang YK, Pyun SB. Clinical efficacy of overground powered exoskeleton for gait training in patients with subacute stroke: A randomized controlled pilot trial. *Medicine*. 2023;102(4):e32761. doi:10.1097/MD.0000000000032761

6. 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

7. Wiśniowska-Szurlej A, Wołoszyn N, Brożonowicz J, et al. Enhanced Rehabilitation Outcomes of Robotic-Assisted Gait Training with EksoNR Lower Extremity Exoskeleton in 19 Stroke Patients. *Med Sci Monit*. 2023;29. doi:10.12659/MSM.940511

8. 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

9. 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

10. Nolan KJ, Ames GR, Dandola CM, et al. Intensity Modulated Exoskeleton Gait Training Post Stroke. In: *2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE; 2023:1-4. doi:10.1109/EMBC40787.2023.10340452

11. Schuster-Amft C, Kool J, Möller JC, et al. Feasibility and cost description of highly intensive rehabilitation involving new technologies in patients with post-acute stroke—a trial of the Swiss RehabTech Initiative. *Pilot Feasibility Stud*. 2022;8(1):139. doi:10.1186/s40814-022-01086-0

12. 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

13. 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

14. 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

15. 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

16. Lorusso M, Tramontano M, Casciello M, et al. Efficacy of Overground Robotic Gait Training on Balance in Stroke Survivors: A Systematic Review and Meta-Analysis. *Brain Sci*. 2022;12(6):713. doi:10.3390/brainsci12060713

17. 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

18. Zhang B, Wong KP, Kang R, Fu S, Qin J, Xiao Q. Efficacy of Robot-Assisted and Virtual Reality Interventions on Balance, Gait, and Daily Function in Patients With Stroke: A Systematic Review and Network Meta-analysis. *Archives of Physical Medicine and Rehabilitation*. 2023;104(10):1711-1719. doi:10.1016/j.apmr.2023.04.005

19. 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

20. 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

21. Hohl K, Smith AC, Macaluso R, et al. Muscle adaptations in acute SCI following overground exoskeleton + FES training: A pilot study. *Front Rehabilit Sci*. 2022;3:963771. doi:10.3389/fresc.2022.963771

22. Tsai CY, Asselin PK, Hong E, et al. Exoskeletal-assisted walking may improve seated balance in persons with chronic spinal cord injury: a pilot study. *Spinal Cord Ser Cases*. 2021;7(1):20. doi:10.1038/s41394-021-00384-8

23. 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

24. Jang TG, Choi SH, Yu SH, Kim DH, Han IH, Nam KH. Exoskeleton-assisted Gait Training in Spinal Disease With Gait Disturbance. *Korean J Neurotrauma*. 2022;18(2):316-323. doi:10.13004/kjnt.2022.18.e25

25. 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

26. Bach Baunsgaard C, Vig Nissen U, Katrin Brust A, et al. Gait training after spinal cord injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics. *Spinal Cord*. 2018;56(2):106-116. doi:10.1038/s41393-017-0013-7

27. 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

28. 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

29. 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

30. 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

31. Quintero HA, Farris RJ, Goldfarb M. A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons with Paraplegia. *J Med Device*. 2012;6(4):0410031-0410036. doi:10.1115/1.4007181

32. 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

33. 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

34. Koljonen PA, Virk AS, Jeong Y, et al. Outcomes of a Multicenter Safety and Efficacy Study of the SuitX Phoenix Powered Exoskeleton for Ambulation by Patients With Spinal Cord Injury. *Front Neurol*. 2021;12:689751. doi:10.3389/fneur.2021.689751

35. Mazzoleni S, Battini E, Rustici A, Stampacchia G. An integrated gait rehabilitation training based on Functional Electrical Stimulation cycling and overground robotic exoskeleton in complete spinal cord injury patients: Preliminary results. In: *2017 International Conference on Rehabilitation Robotics (ICORR)*. IEEE; 2017:289-293. doi:10.1109/ICORR.2017.8009261

36. 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

37. Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A. Safety and tolerance of the ReWalk™ 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

38. 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

39. Raab K, Krakow K, Tripp F, Jung M. Effects of training with the ReWalk exoskeleton on quality of life in incomplete spinal cord injury: a single case study. *Spinal Cord Ser Cases*. 2016;2(1):15025. doi:10.1038/scsandc.2015.25

40. 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

41. 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

42. 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

43. 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

44. 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

45. Berriozabalgoitia R, Bidaurrazaga-Letona I, Otxoa E, Urquiza M, Irazusta J, Rodriguez-Larrad A. Overground Robotic Program Preserves Gait in Individuals With Multiple Sclerosis and Moderate to Severe Impairments: A Randomized Controlled Trial. *Archives of Physical Medicine and Rehabilitation*. 2021;102(5):932-939. doi:10.1016/j.apmr.2020.12.002

46. 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

47. Russo M, Maggio MG, Naro A, et al. Can powered exoskeletons improve gait and balance in multiple sclerosis? A retrospective study. *International Journal of Rehabilitation Research*. 2021;44(2):126-130. doi:10.1097/MRR.0000000000000459

48. Drużbicki M, Guzik A, Przysada G, et al. Effects of Robotic Exoskeleton-Aided Gait Training in the Strength, Body Balance, and Walking Speed in Individuals With Multiple Sclerosis: A Single-Group Preliminary Study. *Arch Phys Med Rehabil*. 2021;102(2):175-184. doi:10.1016/j.apmr.2020.10.122

49. 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

50. Wee SK, Ho CY, Tan SL, Ong CH. Enhancing quality of life in progressive multiple sclerosis with powered robotic exoskeleton. *Mult Scler*. 2021;27(3):483-487. doi:10.1177/1352458520943080

51. 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

52. Karunakaran KK, Nisenson DM, Nolan KJ. Alterations in Cortical Activity due to Robotic Gait Training in Traumatic Brain Injury. *Annu Int Conf IEEE Eng Med Biol Soc*. 2020;2020:3224-3227. doi:10.1109/EMBC44109.2020.9175764

53. Gavrila Laic RA, Firouzi M, Claeys R, Bautmans I, Swinnen E, Beckwée D. A State-of-the-Art of Exoskeletons in Line with the WHO's Vision on Healthy Aging: From Rehabilitation of Intrinsic Capacities to Augmentation of Functional Abilities. *Sensors (Basel)*. 2024;24(7):2230. doi:10.3390/s24072230

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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	J Neurotrauma. 2024 Sep;41(17-18):2089-2100	Ekso	SCI
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
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
A State-of-the-Art of Exoskeletons in Line with the WHO's Vision on Healthy Aging: From Rehabilitation of Intrinsic Capacities to Augmentation of Functional Abilities.	Gavrila Laic RA, Firouzi M, Claeys R, Bautmans I, Swinnen E, Beckwée D.	Sensors (Basel). 2024 Mar 30;24(7):2230	Multiple – Review Article	SCI
Efficacy of robot-assisted and virtual reality interventions on balance, gait, and daily function in patients with stroke: A systematic review and network meta-analysis	Zhang B, Wong KP, Kang R, Fu S, Qin J, Xiao Q	Arch Phys Med Rehabil. 2023 Oct;104(10):1711-1719	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
Enhanced Rehabilitation Outcomes of Robotic-Assisted Gait Training with EksoNR Lower Extremity Exoskeleton in 19 Stroke Patients	Wiśniowska-Szurlej A, Wołoszyn N, Brożonowicz J, Ciąpała G, Pietryka K, Grzegorczyk J, Leszczak , Ćwirlej-Sozańska A, Sozański B, Korczowski B	Med Sci Monit. 2023 Jul 15:29:e940511	Ekso	CVA
Intensity Modulated Exoskeleton Gait Training Post Stroke	Nolan KJ, Ames GR, Dandola CM, Breighner JE, Franco S, Karunakaran KK, Saleh S.	Annu Int Conf IEEE Eng Med Biol Soc. 2023 Jul: 2023:1-4	Ekso	CVA

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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
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
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
Clinical efficacy of overground powered exoskeleton for gait training in patients with subacute stroke: A randomized controlled pilot trial	Yoo HJ, Bae CR, Jeong H, Ko MH, Kang YK, Pyun SB	Medicine (Baltimore). 2023 Jan 27;102(4):e32761	ExoAtlet	CVA
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
Muscle adaptations in acute SCI following overground exoskeleton + FES training: A pilot study	Hohl K, Smith AC, Macaluso R, Giffhorn M, Prokup S, O'Dell DR, Kleinschmidt L, Elliott JM, Jayaraman A	Front Rehabil Sci. 2022 Oct 13:3:963771	Ekso	SCI
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
Feasibility and cost description of highly intensive rehabilitation involving new technologies in patients with post-acute stroke	Schuster-Amft C, Kool J, Moller JC, Schweinfurther R, Ernst MJ, Reicherzer L, Ziller C, Schwab ME, Wieser S, Wirz M	Pilot Feasibility Stud. 2022 Jul 5;8(1):139	Multiple	CVA

All known articles assessing balance 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
Efficacy of Overground Robotic Gait Training on Balance in Stroke Survivors: A Systematic Review and Meta-Analysis	Lorusso M, Tramontano M, Casciello M	Brain Sci. 2022 May 31;12(6):713v	Multiple – Review Article	CVA
Exoskeleton-assisted Gait Training in Spinal Disease With Gait Disturbance	Jang TG, Choi SH, Yu SH, Kim DH, Han IH, Nam KH.	Korean J Neurotrauma. 2022 May 2;18(2):316-323	ExoAtlet	SCI
Brain Network Organization Following Post-Stroke Neurorehabilitation	Naro A, Pignolo L, Calabrò RS	Int J Neural Syst. 2022 Apr;32(4):2250009	Ekso	CVA
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
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

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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	Phoenix	SCI
Can powered exoskeletons improve gait and balance in multiple sclerosis? A retrospective study	M Russo, M Grazia Maggio, A Naro, S Portaro, B Porcari, T Balletta, R De Luca, L Raciti, RS Calabrò	Int J Rehabil Res. 2021 Jun 1;44(2):126-130	Ekso	MS
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
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
Overground Robotic Program Preserves Gait in Individuals With Multiple Sclerosis and Moderate to Severe Impairments: A Randomized Controlled Trial	R Berriozabalgoitia, I Bidaurrazaga-Letona, Otxoa E, Urquiza M, Irazusta J, Rodriguez-Larrad A	Arch Phys Med Rehabil. 2021 May;102(5):932-939	Ekso	MS
Exoskeletal-assisted walking may improve seated balance in persons with chronic spinal cord injury: a pilot study	Tsai CY, Asselin PK, Hong E, Knezevic S, Kornfeld SD, Harel NY, Spungen AM	Spinal Cord Ser Cases. 2021 Mar 12;7(1):20	ReWalk	SCI
Enhancing quality of life in progressive multiple sclerosis with powered robotic exoskeleton	Wee SK, Ho CY, Tan SL, Ong CH	Mult Scler. 2021 Mar;27(3):483-487	Ekso	MS
Effects of Robotic Exoskeleton aided gait training in the strength, body balance and walking speed in subjects with multiple sclerosis - a single-group, preliminary study	Drużbicki M, Guzik A, Przysada G, Perenc L, Brzozowska-Magoń A, Cygoń K, Boczula G, Bartosik-Psujek H	Arch Phys Med Rehabil. 2021 Feb;102(2):175-184	Ekso	MS
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
Does overground robotic gait training improve non-motor outcomes in patients with chronic stroke? Findings from a pilot study	De Luca R, Maresca G, Balletta T, Cannavò A, Leonardi S, Latella D, Maggio MG, Portaro S, Naro A, Calabrò RS	J Clin Neurosci. 2020 Nov:81:240-245.	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

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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, Gorman,Forrest, Asselin, Knezevic, Scott, Wojciehowski, Kornfeld, Spungen	Front Robot AI. 2020 Aug 4:7:93	ReWalk, Ekso	SCI
Alterations in Cortical Activity due to Robotic Gait Training in Traumatic Brain Injury	Karunakaran KK, Nisenson DM, Nolan KJ	Annu Int Conf IEEE Eng Med Biol Soc. 2020 Jul:2020:3224-3227	Ekso	ABI
Exoskeleton-assisted Gait Training in Persons With Multiple Sclerosis: A Single-Group Pilot Study	Afzal T, Tseng SC, Lincoln JA, Kern M, Francis co GE, Chang SH	Arch Phys Med Rehabil. 2020 Apr;101(4):599-606	Ekso	MS
Effects of Exoskeleton Gait Training on Balance, Load Distribution, and Functional Status in Stroke: A Randomized Controlled Trial	Rojek A, Mika A, Oleksy L, Stolarczyk A, Kielnar R	Front Neurol. 2020 Jan 15:10:1344.	Ekso	CVA
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 fro m 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
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
Shaping neuroplasticity by using powered exoskeletons in patients with stroke: a randomized clinical trial	Calabrò RS, Naro A, Russo M, Bramanti P, Carioti L, Balletta T, Buda A, Manuli A, Filoni S, Bramanti A.	J Neuroeng Rehabil. 2018 Apr 25;15(1):35	Ekso	CVA

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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
Gait training after spinal cord injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics.	Bach Baunsgaard C, Vig Nissen U, Katrin Brust A, Frotzler A, Ribeill C, Kalke YB, León N, Gómez B, Samuelsson K, Antepohl W, Holmström U, Marklund N, Glott T, Opheim A, Benito J Murillo N, Nachtegaal J, Faber W, Biering-Sørensen F	Spinal Cord. 2018 Feb;56(2):106-116	Ekso	SCI
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
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
Effects of training with the ReWalk exoskeleton on quality of life in incomplete spinal cord injury: a single case study	Raab K, Krakow K, Tripp F and Jung M	Spinal Cord Ser Cases. 2016 Jan 7:2:15025	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	ReWalk	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 Feasibility of Using the Ekso™ Bionic Exoskeleton to Aid Ambulation after Spinal Cord Injury	Kolakowsky-Hayner SA, Crew J, Moran S, Shah A	J Spine 2013, S4	Ekso	SCI
A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons With Paraplegia	Quintero HA, Farris RJ, Goldfarb M	J Med Device. 2012 Dec 12;6(4):0410031-0410036	Indego	SCI

All known articles assessing balance in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Safety and tolerance of the ReWalkTM 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