Speed

Gait speed is one of the most reported on outcomes in the body of research looking at robotic exoskeletons. The majority look at subjects with spinal cord injury (45 articles) followed by stroke (26 articles). Most articles were case series, though there were also a number of review articles (24) that examined gait speed. Most articles used the 10 Meter Walk Test (10MWT) to measure gait speed, with this measure being used in 72% of trials. Of studies that utilized a single device, Ekso1.1/GT/NR device, referred to as "Ekso" in this paper, was used the most (33 articles), followed by ReWalk (8) and Indego (6).

Spinal Cord Injury (SCI)

Like most of the research on exoskeletons, the majority of research looking at walking speed is completed with patients with SCI.

There are a few randomized controlled trials (RCTs) that examine gait speed measured outside of the exoskeleton, some of which compared exoskeletons to other treatment methods. One study randomized participants with chronic incomplete SCI to receive either Ekso (n=9), body weight support treadmill training (BWSTT) (n=10), or their normal daily activities (n=6) for 12 weeks.[1] Self-selected gait speed increased by 51% in the Ekso group, 32% in the BWSTT group, and 14% in the normal activities group.[1] When looking at which group had the most responders, meaning those who improved gait speed beyond the Minimal Clinically Important Difference (MCID) of 0.15 m/s, the Ekso group was victorious, with 33% reaching that metric, compared to 20% in the BWSTT group and 0% in the normal activities group.[1] The other RCT compared Ekso to conventional gait training. It used seven participants with chronic motor incomplete injuries to receive treatment for 15 sessions over 3 weeks. No statistically significant difference was found between the two groups in the mean difference between pre and post assessments, however, this was complicated by significant between group differences in gait speed at baseline.[2]

Some studies noted improvement in gait speed outside of a device when comparing testing completed pre-exoskeleton intervention to that completed post-exoskeleton intervention. One study showed this improvement only in the subgroup that was recently injured and not in the chronically injured group.[3] Another study of 3 subjects that completed 20 sessions of Ekso training improved their velocity from 0.17±0.04m/s to 0.23±0.04m/s, which was a statistically significant change.[4] Another reported that average gait speed increased by 2.1 times between sessions 1 and 12.[5]

Some studies, especially those using non-ambulatory subjects, completed gait speed assessments while subjects were wearing an exoskeleton. One such study was a crossover design that randomized 10 participants with chronic motor complete SCI to receive 10 sessions each of gait training with ABLE and with knee-ankle-foot orthoses (KAFOs). There was no significant difference between using ABLE and KAFOs in terms of gait speed.[6] A case study comparing walking with KAFOs and Indego demonstrated the opposite: that walking was significantly faster in the Indego, around 0.17 m/s as compared to 0.1 m/s in KAFOs.[7] Another study was a crossover trial that assigned people to 12 weeks of Ekso or ReWalk walking and 12 weeks of usual activity, randomized for which they received first. Most participants improved gait speed, with 34% exceeding 0.4 m/s.[8]

Studies also reported different speeds that the subjects were able to walk in an exoskeleton. Community gait speed was defined as 0.49 m/s.[9] Most of these studies utilized participants with complete SCI. Studies reported a range of gait speeds in exoskeletons, with most reporting speeds between 0.1-0.4 m/s. [10–19] Other studies included speed ranges that were faster than 0.4 m/s[20–22] or slower than 0.1 m/s.[23] The fastest speed noted in the literature was 0.71 m/s and was tested in the ReWalk.[22] One review reported the average speed among all exoskeletons at 0.31 m/s[24], while another reported a slightly slower 0.26 m/s.[25] One study broke down speed in the Indego by level of injury, with those with motor complete tetraplegia walking at a speed of 0.22 m/s, those with upper thoracic motor complete injuries walking at 0.26 m/s, and those with lower thoracic motor complete injuries walking at 0.45 m/s.[26] Level of injury was also shown to impact speed of walking in ReWalk, with lower injuries walking at a faster speed of 0.21 m/s and those with higher level injuries walking at 0.12 m/s.[27]

Some studies examined how walking speed in an exoskeleton changed as participants became more proficient and independent at using the device. One study showed a 52% increase in speed while walking in the exoskeleton, though this was over 100 hours of training[28], while a similar dosage in another study only showed a 30% increase in speed.[29] When comparing an early Ekso walking session (session #4) to a later one (session #20), an increase in walking speed was found, however, it was not statistically significant.[30] This is directly contrary to another study that showed participants walking 3.2 times faster during their 25th training session versus session 2, reaching speeds averaging 0.4 m/s by the end of the study.[31]

Other studies examined gait speed in or resulting from use of an exoskeleton in combination with another treatment method including epidural stimulation.[32] Another study looked at Ekso use in sequence with lower limb Functional Electrical Stimulation (FES), receiving 20 sessions of each in randomized order. In the group that received exoskeleton walking first, 10MWT improved by 30% after exoskeleton training, but no further improvement was noted with the subsequent FES sessions.[33]

There are multiple review articles focusing on people with SCI. Most have mixed results on how exoskeleton usage affects gait speed. Some report thatthere is no difference between training in an exoskeleton and a control treatment[34,35] while others report speed improvements resulting from using an exoskeleton.[36–39] Others reported improvements either only or more significantly in specific subgroups of persons with SCI, such as those with acute injuries.[35,39] One review compared a wearable exoskeleton to the Lokomat and determined that the probability of the wearable device ranking first in improving gait speed was 89%.[40] Another review examined factors that might influence gait speed in non-ambulatory individuals using an exoskeleton. These included age, injury duration, injury level, and number of training sessions, and found that more sessions, greater age, and lower level of injury correlated with faster gait speed.[25]

Stroke (CVA)

The research in subjects with CVA measures changes in gait speed as a result of an exoskeleton intervention, with outcomes measured without the exoskeleton. This body of research begins strongly with six randomized controlled trials, all of which utilize Ekso. With equal training time, 40 subjects were allocated with a 1:1 ratio to receive treatment 5 days a week for 8 weeks. Those who received Ekso training met the Minimal Detectable Change (MDC) for 10MWT whereas those who received only conventional treatment did not.[41] Thirty participants with chronic CVA were assigned to receive Ekso or physical therapist aided gait training 3 times a week for 8 weeks. The group receiving Ekso gait training improved median gait speed by 0.4 m/s whereas the conventional treatment group only improved by a median of 0.1 m/s.[42] Participants with subacute stroke were randomized to receive conventional (n=9) or ExoAtlet (n=16) training three times per week for 4 weeks in addition to 5 times a week traditional therapy. Median gait speed improved in the ExoAtlet group by 0.28 m/s whereas it did not improve in the conventional therapy only group.[43] Another article randomized 40 persons with chronic stroke with a 1:1 allocation to receive Ekso or conventional training on all weekdays for 8 weeks and demonstrated superiority of the Ekso for increasing gait speed measured by the 10MWT.[44] All subjects in the Ekso group surpassed the MCID whereas only 40% of those in the conventional training group met this metric.[44] However, a similar study of 75 subjects with subacute CVA who received 5 sessions per week for 3 weeks of either Ekso or conventional gait training showed improvements in both groups that were not significantly different.[45] These studies were all completed in a research setting, where dosage was higher than what can be expected in an insurance-based healthcare system. The final known randomized controlled trial was completed in the rehab setting, where patients with subacute CVA of less than 3 months who were unable to walk (Functional ambulation capacity of 0-1) were randomized to receive standard physical therapy or Ekso training until discharge, where this method was to replace 75% of physical therapy time, which roughly amounted to 3 sessions per week for 60 minutes per session. Some of the participants in the Ekso group declined further intervention and therefore results were analyzed as-treated, with the Ekso group (n=14) reigning superior to the usual care group (n=22) in terms of improving gait speed between discharge and 6-month follow-up.[46]

Another study completed in the setting of inpatient rehabilitation examined 14 subjects with moderate to severe CVA who received both standard of care and Ekso training and found that 12 participants showed improvement with gait speed measured by the 10MWT. [47] There was a moderate correlation between number of robotic sessions and change in speed.[47]

While not conducted in a rehabilitation setting, there are a few other studies that employed a smaller dosage of robotic training. One of these used Indego in a clinical setting for four sessions over two weeks in 8 patients with acute stroke and 30 with chronic stroke. Walking speed for the chronic group significantly increased from 0.16±0.54 m/s to 0.26±1.59 m/s.[48] A similar increase was seen in the acute group, improving from 0.13±1.09 m/s to 0.24±1.16 m/s.[48] Another study looked at changes resulting from a single session of walking in Ekso using a motion capture system and showed that 6 participants with chronic CVA improved speed by 0.01 m/s, which is a small, insignificant change.[49]

The remainder of the research using subjects post stroke is completed in a research setting, mostly with a pre-post design. Some studies showed positive improvements when comparing baseline to post-intervention. One such study utilized 46 patients with strokes that occurred 2 weeks to 6 months before and assigned them to use Ekso for an average of 15±2 sessions over 3 to 5 weeks. Thirty-two participants were ambulant at the study start and these participants improved their gait speed measured by 10MWT significantly from 0.31±0.22 m/s to 0.46±0.25

m/s.[50] A study with slightly shorter dosage of 12 Ekso sessions offered 3 times per week for persons with subacute (n=12) and chronic (n=11) stroke showed significant change in walking velocity from baseline to conclusion of all Ekso sessions in both the subacute and chronic subgroups.[51] A small study of 2 patients with acute CVA who walked for 30 minutes, three times a week for 10 weeks in Ekso showed improvement of walking speed by 0.74 and 1.0 m/s.[52]

Other studies, however, showed no significant changes between baseline and post-intervention. A study that showed no significant change tested 8 subjects who were able to walk without assistance prior to 15 sessions of Ekso training over 3 weeks. The average change in gait speed was 0.22±0.34 m/s with a p value of 0.11, which is approaching significance.[53] Another study showing no change in gait speed had subjects complete 12.6±1.95 sessions of Ekso walking over 25.6±12.1 days.[54]

One study looked at exoskeletons as part of a high intensity technology assisted training program for persons post CVA. Fourteen patients exercised for 12-21 days, receiving between 28-82 technology-assisted sessions and improved their average gait speed from 0.40 to 0.47 m/s.[55]

There are also a number of review articles that comment on gait speed in persons with stroke. Some reviews showed that exoskeletons improve gait speed at end of intervention[56–58], while others did not show significant differences at end of intervention[59,60] or at follow up.[56,57,59] Other reviews reported on mixed results of the individual studies included and did not determine a firm conclusion as to whether gait speed is significantly affected by use of an exoskeleton.[61] When different treatment methods were compared, one review concluded that the best at improving gait speed was conventional therapy plus body weight support training plus robotic gait training[62] while another article stated that it was a combination of robotic assisted training and virtual reality.[63] Another review noted that over ground exoskeletons resulted in a faster gait velocity, whereas treadmill-based devices resulted in no difference in relation to controls.[58]

Multiple Sclerosis (MS)

Only a few articles exist on how exoskeletons can impact speed in persons with MS. Two of these are randomized controlled trials. The first is a small study of four subjects with relapsing-remitting MS who were randomized to either complete eight sessions of gait training using Ekso or conventional therapy. When tested with the Timed 25 Foot Walk (T25FW), the Ekso group (n=18) improved by 15% while the control group improved only by 8%.[64] The other study had all 36 participants complete weekly 1-hour physical therapy sessions over 3 months, with the Ekso group receiving an additional 2 sessions per week of exoskeleton training. Results showed that the control group increased the time it took to complete the 10MWT by an average of 1.22 seconds, which was statistically significant, while the Ekso group increased by an average of 0.59 seconds, which was not statistically significant.[65] This suggests that exoskeleton walking could preserve gait function as opposed to the typical decline we expect to see with MS.

Other studies, while not all controlled, also agreed that treatment with an exoskeleton either increased gait speed in persons with MS or prevented the slowing of gait speed typical in this diagnosis. A retrospective study examined 20 patients who either received treatment with Ekso or traditional gait training. These participants were matched for age, sex, duration of disease, and Expanded Disability Status Scale (EDSS). Only in the group receiving Ekso did the gait speed measured by 10MWT significantly improve by 0.85 seconds versus a 0.68 second decline in the control group.[66] Fourteen individuals with EDSS from 5 to 6.5 (disability affects full daily activities, can walk 20-200m without resting, may use walking aid) completed 15 sessions of Ekso over three weeks and showed significant increase in gait speed from baseline, 0.7 m/s, to completion of Ekso sessions, 0.87 m/s, measured by T25FW.[67] Another study used 10 subjects with more severe disability, EDSS between 6-7.5, which means that at minimum, they require a walking aid or they utilize a wheelchair but can self-propel. They walked for 15 sessions in the Ekso over three weeks and during this time, gait speed measured with the T25FW improved from 0.35±0.18 m/s to 0.42±0.23 m/s, which was statistically significant.[68] Interestingly, another study with a longer intervention of 3 times walking in ReWalk per week for 8 weeks, only had 5 of 13 participants complete the protocol and none improved on speed.[69]

One review focused on subjects with MS and reported that robotic treatment had a positive effect on gait speed, though these findings were not significantly different than those reported from conventional therapy.[70] Another review showed significant improvement after robotic intervention with regard to walking velocity.[61]

Acquired Brain Injury

Only three articles exist that specifically focus on subjects with ABI and two primarily focus on spatiotemporal characteristics of gait but did measure speed via a Zeno walkway. In one study comparing two individuals with ABI and one reference healthy control, walking with Ekso for 2-3 days per week for four weeks as an outpatient resulted in increased walking speed for the ABI group outside of the exoskeleton, though it was still slower than the healthy control.[71] The other article used a similar frequency of treatment at three times per week of Ekso walking over four weeks. Seven subjects completed the protocol, and five of those improved their gait speed from baseline to completion of the intervention.[72] A case study participant who underwent four weeks of Ekso training improved his gait speed from 0.68 m/s to 0.74 m/s.[73]

Review Articles

One review article examined older adults with a variety of diagnoses that utilized different exoskeletons. Maximum walking speed and self-selected gait speed increased after exoskeleton training.[74]

Conclusion

Most articles report an improvement in gait speed from using an exoskeleton, and none noted a worsening of gait speed, with the exception of articles examining persons with MS who worsened less so than controls. Inconclusive results may have been due to different exoskeleton devices being used and varying dosage of intervention.

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All known articles assessing speed 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
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	Multiple – Review Article
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
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
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
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

All known articles assessing speed 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
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
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
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
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	Lokomat, 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, Chaverri D, Iglesias X, Guirao-Cano L, Font-Llagunes JM	Sci Rep. 2022 Nov 9;12(1):19150	Able	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 speed 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
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
Changes in Center of Pressure after Robotic Exoskeleton Gait Training in Adults with Acquired Brain Injury	Karunakaran KK, Pamula S, Nolan KJ	Annu Int Conf IEEE Eng Med Biol Soc. 2021 Nov:2021:4666-4669	Ekso	ABI
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 speed 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
Utilization of Robotic Exoskeleton for Overground Walking in Acute and Chronic Stroke	Nolan KJ, Karunakaran KK, Roberts P, Tefertiller C, Walter AM, Zhang J, Leslie D, Jayaraman A and Francisco GE	Front Neurorobot. 2021 Sep 1:15:689363	Indego	CVA
Evaluation of safety and performance of the self balancing walking system Atalante in patients with complete motor spinal cord injury	Kerdraon J, Previnaire JG, Tucker M, Coignard P, Allegre W, Kanppen E, Ames A	Spinal Cord Ser Cases. 2021 Aug 4;7(1):71	Atalante	SCI
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
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
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
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

All known articles assessing speed in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Functional Gait Recovery after a Combination of Conventional Therapy and Overground Robot-Assisted Gait Training Is Not Associated with Significant Changes in Muscle Activation Pattern: An EMG Preliminary Study on Subjects Subacute Post Stroke	Infarinato F, Romano P, Goffredo M, Ottaviani M, Galafate D, Gison A, Petruccelli S, Pournajaf S, Franceschini M	Brain Sci. 2021 Apr 1;11(4):448	Ekso	CVA
Effect of robotic-assisted gait training on objective biomechanical measures of gait in persons post-stroke, a systematic review and meta-analysis	Nedergard H, Arumugam A, Sandlund M, Brandal A, Hager CK	J Neuroeng Rehabil. 2021 Apr 16;18(1):64	Multiple – Review Article	CVA
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
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
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
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, Glize B, Bouyer L, Dehail P, Cassoudesalle H	Ann Phys Rehabil Med. 2020 Nov;63(6):518-534	Multiple – Review Article	CVA
Kinetic Gait Changes after Robotic Exoskeleton Training in Adolescents and Young Adults with Acquired Brain Injury	Karunakaran KK, Ehrenberg N, Cheng J, Bentley K, Nolan KJ	Appl Bionics Biomech. 2020 Oct 27:2020:8845772	Ekso	ABI

All known articles assessing speed in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Immediate kinematic and muscle activity changes after a single robotic exoskeleton walking session post-stroke.	Swank C, Almutairi S, Wang-Price S, Gao F.	Top Stroke Rehabil. 2020 Oct;27(7):503-515	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
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
The feasibility of using exoskeletal-assisted walking with epidural stimulation: a case report study	Gorgey AS, Gill S, Holman ME , Davis JC, Atri R, Bai O, Goetz L, Lester DL, Trainer R, Lavis TD	Ann Clin Transl Neurol. 2020 Feb;7(2):259-265	Ekso	SCI
The safety and feasibility of exoskeletal assisted walking in acute rehabilitation following 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
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

All known articles assessing speed in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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, Molteni F	Eur J Phys Rehabil Med. 2019 Apr;55(2):209-216	ReWalk	SCI
Overground walking with a robotic exoskeleton elicits trunk muscle activity in people with high-thoracic motor-complete spinal cord injury	Alamro RA, Chisholm AE, Williams AMM, Carpenter MG, Lam T	J Neuroeng Rehabil. 2018 Nov 20;15(1):109	Ekso	SCI
Exoskeleton and End-Effector Robots for Upper and Lower Limbs Rehabilitation: Narrative Review	Molteni F, Gasperini G, Cannaviello G, Guanziroli E	PM R. 2018 Sep;10(9 Suppl 2):S174-S188	Multiple – Review Article	CVA, SCI
Neuromechanical adaptations during a robotic powered exoskeleton assisted walking session	Ramanujam A, Cirnigliaro CM, Garbarini E, Asselin P, Pilkar R, Forrest GF	J Spinal Cord Med. 2018 Sep;41(5):518-528	Ekso	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
Effects of Exoskeleton Training Intervention on Net Loading Force in Chronic Spinal Cord Injury	Husain SR, Ramanujam A, Momeni K, Forrest GF	Annu Int Conf IEEE Eng Med Biol Soc. 2018 Jul:2018:2793-2796	Ekso	SCI
Robotic Rehabilitation and Spinal Cord Injury a Narrative Review	Mekki M, Delgado AD, Fry A, Putrino D, Huang V	Neurotherapeutics. 2018 Jul;15(3):604-617	Multiple – Review Article	SCI
Mechanisms for improving walking speed after longitudinal powered robotic exoskeleton training for individuals with spinal cord injury	Ramanujam A, Momeni K, Husain SR, Augustine J, Garbarini E, Barrance P, Spungen A, Asselin P, Knezevic S, Forrest GF	Annu Int Conf IEEE Eng Med Biol Soc. 2018 Jul:2018:2805-2808	Ekso	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 speed 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
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
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
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
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
Training Response to Longitudinal Powered Exoskeleton Training for SCI	Ramanujam A, Spungen A, Asselin P, Garbarini E, Augustine J, Canton S., Barrance P., Forrest GF	Wearable Robotics: Challenges and Trends, 2017, Volume 16	Ekso, ReWalk	SCI
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
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

All known articles assessing speed in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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
Gait speed using powered robotic exoskeletons after spinal cord injury: a systematic review and correlational study	Louie DR, Eng JJ, Lam T	J Neuroeng Rehabil. 2015 Oct 14:12:82	Multiple – Review Article	SCI
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
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
Mobility Outcomes Following Five Training Sessions with a Powered Exoskeleton	Hartigan C, Kandilakis C, Dalley S, Clausen M, Wilson E, Morrison S, Etheridge S, Farris R.	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):93-9	Indego	SCI
Acute Cardiorespiratory and Metabolic Responses During Exoskeleton-Assisted Walking Overground Among Persons with Chronic Spinal Cord Injury	Evans N, Hartigan C, Kandilakis C, Pharo E, Clesson I	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):122-32	Indego	SCI
Understanding Therapeutic Benefits of Overground Bionic Ambulation: Exploratory Case Series in Persons With Chronic, Complete Spinal Cord Injury	Kressler J, Thomas CK, Field-Fote EC, Sanchez J, Widerström-Noga E, Cilien DC, Gant K, Ginnety K, Gonzalez H, Martinez A, Anderson KD, Nash MS	Arch Phys Med Rehabil. 2014 Oct;95(10):1878-1887.e4	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, Goldfarb M	IEEE Trans Neural Syst Rehabil Eng. 2014 May;22(3):482-90	Indego	SCI
The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury	Esquenazi A, Talaty M, Packel A, Saulino M	Am J Phys Med Rehabil. 2012 Nov;91(11):911-21	ReWalk	SCI
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

All known articles assessing speed in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals	Farris RJ, Quintero HA, Goldfarb M	IEEE Trans Neural Syst Rehabil Eng. 2011 Dec;19(6):652-9	Indego	SCI

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