Strength

Some research articles include strength as a secondary outcome measure when examining use of exoskeletons. There is almost an even split between papers that recruited participants with stroke (10) and spinal cord injury (8). Most articles are a pre-post design where outcomes were tested in one group of participants before and after intervention. While some articles, especially review articles, included multiple types of exoskeleton devices, the papers that only looked at one device evaluated exclusively the Ekso1.1/GT/NR device, referred to as "Ekso" in this paper. Strength is measured in different ways in these studies, with the most common outcome measures including the Motricity Index (MI), Lower Extremity Motor Score (LEMS), Manual Muscle Test (MMT), and Fugl-Meyer.

Studies Completed in Inpatient Rehabilitation

One study included patients in an inpatient rehabilitation facility who had recent strokes (CVA) or spinal cord injuries (SCI). Twenty-five patients used the Ekso an average of 4.5 sessions (range: 2-13) during their average 38.5 day rehabilitation stay. MMT was completed throughout upper and lower extremities and several changes between baseline and discharge strength were significant for some muscles, primarily in the lower extremities.[1] Muscle groups that increased significantly in strength bilaterally were hip flexors, knee extensors, ankle dorsiflexors, and ankle plantarflexors.[1] In this study sample, the average left leg strength was lower than the right, and therefore additional muscle groups showed significant changes only on the left side.[1] These included the hip abductors and hip flexors.[1] Another study was completed in inpatient rehabilitation with participants with SCI. This retrospective study compared 10 subjects who received Ekso as part of their normal 15 hours of therapy per week and 20 historical matched controls. Changes in Upper Extremity Motor Scores (UEMS) were higher in the intervention group although this change was not statistically significant from the controls.[2] There was greater improvement in the LEMS in the intervention group (14.3±10.1) that was significantly greater than the control group (4.6±6.1).[2] This difference in LEMS score was still significant once days of inpatient stay were controlled for.[2] A Canadian study where subjects post-CVA who were unable to walk without substantial assistance were randomized to receive either exoskeleton based training or standard physical therapy for 75% of their standard physical therapy sessions showed that those treated with an exoskeleton improved more significantly on the lower extremity Fugl-Meyer score at discharge.[3]

Stroke (CVA)

A few articles using subjects with CVA were randomized controlled trials (RCTs) which compared exoskeleton treatment to another treatment. One compared exoskeleton gait training to conventional physical therapy. In one such study, strength was assessed using the MI in 75 subjects with subacute CVA who received 15 sessions of gait training either conventionally or with Ekso. Both groups improved in strength, but there was no significant benefit of one treatment method over the other.[4] The other compared two types of robotics, with all 32 participants with chronic stroke receiving 8 weeks of conventional therapy followed by gait training provided either by ExoAtlet or Lokomat devices. There was no difference between robotic device used in the way that strength improved measured by the 30 second sit-to-stand test.[5]

Other pre-post studies examined outcomes before and after exoskeleton intervention. Twenty patients with subacute stroke underwent 15 sessions of Ekso training over 3 weeks which resulted in significant improvement in MI of 18.63±9.35.[6] Forty-six participants who were between 13 and 155 days post CVA completed an average of 15 sessions using Ekso. MI of all muscles measured showed significant improvement for the total population studied.[7] This study also examined results in specific groups based on ambulation level at baseline and study conclusion. Significant strength improvement was seen in those who were ambulant at baseline and those that became ambulant during study.[7] Those who were non-ambulant at baseline and conclusion of the study did not have significant strength improvements.[7] A similar study with 23 subjects who walked thrice per week for 4 weeks in Ekso noted significant improvement in MI scores throughout the study.[8] Median MI scores for those with subacute CVA improved from 33.5 to 59 and for those with chronic CVA from 34 to 38.[8]

One review article that examined subjects with CVA commented on strength changes from using an exoskeleton. Thirty-four RCTs consisting of 1166 patients concluded that the intervention groups had improvement in lower limb motor function scores superior to scores of the control groups.[9]

A unique article which includes many technologies and a highly intensive rehabilitation program for persons with stroke demonstrated that this program consisting of 2 to 7 daily interventions over a period of 12-21 days significantly improved upper extremity strength measured by the Fugl-Meyer from a median 16 to 27.5.[10] Lower extremity strength was not assessed.[10]

Spinal Cord Injury (SCI)

There are numerous studies that examined muscle strength recovery resulting from using an exoskeleton. Most of these utilized LEMS. In one randomized trial of 7 subjects with incomplete SCI, three of the four subjects who received Ekso training improved in LEMS score.[11] The three control subjects either had no change in LEMS score (2) or saw a decrease in LEMS score (1).[11] Another randomized trial of subjects with motor incomplete SCI showed that both Ekso and control groups improved in upper extremity and trunk strength, but only the Ekso group showed a significant increase in lower extremity scores with an average improvement of 3 points over the 24 week intervention period.[12] A pre-post designed study had 52 participants with SCI complete up to 24 Ekso sessions over 8 weeks. The range of sessions completed was 17-24. Only those who were injured recently improved in strength measured by LEMS.[13]

There are two review articles that examine exoskeleton usage in persons with SCI and comment on strength, although neither article had strength as a primary outcome. One review of 19 randomized controlled trials (RCT) involving 770 participants found that individuals with acute incomplete SCI who utilized an exoskeleton improved more on LEMS.[14] For those with chronic injuries, there was no significant difference in strength improvements between a group of subjects with SCI who received exoskeleton treatment versus controls.[14] The second review article synthesized 11 RCTs including 456 subjects. This meta-analysis showed that exoskeleton training was more effective in improving LEMS compared to conventional gait training.[15]

Multiple Sclerosis (MS)

There are a few articles looking at strength changes resulting from using an exoskeleton in persons with MS. One examined 14 subjects with Expanded Disability Status Scale (EDSS) from 5-6.5 (can walk at least 20 meters but is not fully ambulatory) who underwent 15 sessions of Ekso training over three weeks. Knee extensor torque improved significantly over the three weeks of exoskeleton training from 53.81% to 70.77%, but this did not maintain through follow up.[16] Peak knee flexor torque did not change significantly.[16] The work normalized to body weight as well as acceleration time, which is the time to attain isokinetic speed, also improved significantly for extensors.[16] The same number of sessions provided twice weekly was provided to a single subject who was non-ambulatory (EDSS 8). At the hip, the right side improved from no movement to having a palpable contraction.[17] The right knee extensor also improved, progressing from full range of motion against gravity to being able to resist some resistance.[17] A retrospective study showed no difference in lower extremity Motricity Index for those treated with Ekso or traditional therapy.[18]

Review Articles

One review article investigated strength changes resulting from an exoskeleton as part of their analysis. Thirty-six articles utilizing participants aged 65 and above who walked in a variety of robotic technologies were evaluated. It noted that these devices can be used to enhance strength but also to augment current strength, separating use of these robotics into use for rehabilitation and use for augmentation.[19]

Conclusion

Strength, while not a primary outcome measure of any study, has been studied in the context of exoskeleton usage. Most studies agree that exoskeletons can be used to improve strength, especially of the lower extremities. Limitations of this conclusion include the variable intervention duration of these studies as well as, in comparison groups, the lack of a definition for conventional therapy.

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All known articles assessing strength 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
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
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
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
Use of Lower Limb Exoskeletons as an Assessment Tool for Human Motor Performance: A Systematic Review	Moeller T, Moehler F, Krell-Roesch J, Dežman M, Marquardt C, Asfour T, Stein T, Woll A	Sensors (Basel). 2023 Mar 10;23(6):3032	Multiple – Review Article	Multiple – Review Article
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
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
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
Can powered exoskeletons improve gait and balance in multiple sclerosis? A retrospective study	Russo M, Maggio MG, Naro A, Portaro S, Porcari B, Balletta T, De Luca R, Raciti L, Calabrò RS	Int J Rehabil Res. 2021 Jun 1;44(2):126-130	Ekso	MS

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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
Feasibility of integrating robotic exoskeleton gait training in inpatient rehabilitation	Swank C, Sikka S, Driver S, Bennett M, Callender L	Disabil Rehabil Assist Technol. 2020 May;15(4):409-417	Ekso	SCI, CVA
Exoskeletal-Assisted Walking during Acute Inpatient Rehabilitation Leads to Motor and Functional Improvement in Persons with Spinal Cord Injury - a Pilot Study.	Tsai CY, Delgado AD, Weinrauch WJ, Manente N, Levy I, Escalon MX, Bryce TN, Spungen AM	Arch Phys Med Rehabil. 2020 Apr;101(4):607-612	Ekso	SCI
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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

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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

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