Exertion

There are many articles in the literature that evaluate the use of robotic exoskeletons and their effect on exertion across a variety of diagnoses. Most of these publications cover the Ekso 1.1/GT/NR device (47), referred to as “Ekso” in this paper. Other devices used include ReWalk (7), Indego (4), HAL (2), UAN.GO (2), and SuitX Phoenix (1), among others. The most widely studied diagnosis was Spinal Cord Injury (44), followed by Multiple Sclerosis (10), stroke (8) and brain injury (3). The most commonly reported outcome measures in regards to exertion were Borg Rating of Perceived Exertion (RPE) (23), Physiological Cost Index (4), Fatigue Impact Scale (3), and Fatigue Severity Scale (2).

Spinal Cord Injury (SCI)

Some studies that looked at exertion in a population with SCI examined whether exoskeletons could be used as exercise. Thirteen wheelchair users with SCI used Ekso 2-3x/week for 10 weeks and it was found that their cardiorespiratory measures increased 22-52% while walking in the device; oxygen cost, relative HR, relative O_2 consumption, respiratory exchange ratio, and RPE achieved 0.29 mL/kg/m, 82.9%, 41.8%, 0.9 and 3.2/10, respectively, indicating that these users were able to reach a moderate-intensity level of exercise while walking in the Ekso.[1] Another Ekso study with 7 SCI subjects demonstrated that participants were able to achieve mild-to-moderate intensity exercise while using the device, based on heart rate changes and RPE scores ranging from light to somewhat hard.[2] A third Ekso study that compared individuals with SCI to a control group reported RPE scores of “light to moderate” indicating that using the device correlates to “light” exercise. The authors note that although the American College of Sports Medicine recommends moderate to vigorous intensity activity for most adults, there may still be benefits from light to moderate exercise for deconditioned persons with SCI.[3] Two more Ekso studies with a combined 7 subjects also reported “light-to-moderate” RPE scores[4,5] in addition to an 11 subject SCI Ekso study that demonstrated an average “moderate” RPE score.[6] In a randomized controlled trial comparing Ekso to standard care in subjects with SCI, the Ekso group reported Borg RPE scores were as high as 14-15 (rated on a scale of 6-20) which correlates to a high level of effort and thus, higher intensity exercise[7]. Another randomized study in 16 subjects compared Ekso training to activity based therapy and reported lower RPE scores (i.e. less exertion) in the activity based therapy group when compared to the Ekso group at the end of the study.[8] Two individuals with SCI and different baseline functionalities in terms of walking were compared after using the Ekso and it was found that the individual with lower baseline walking capability was able to achieve a higher cardiometabolic challenge while using the device than the individual with a higher baseline walking capability.[9] In a single subject SCI Ekso case study, both assistance from the device and spinal cord epidural stimulation while using the device were varied and it was found that walking with higher levels of spinal cord epidural stimulation in combination with lower assistance levels from the device resulted in the highest RPE (i.e. more exertion) scores of the study; as high as 17.4 ± 1.5 which correlates to “very hard”.[10] A 6 subject SCI study with the ReWalk reported “moderate” fatigue after using the device on a fatigue visual analogue scale (VAS).[11] A second ReWalk study in 5 individuals with SCI reported that fatigue was more severe after ReWalk training sessions based on a VAS fatigue scale.[12] Lastly, the SuitX Phoenix was utilized in a 40 subject SCI study and exertion was measured by both Borg RPE and fatigue.[13] When analyzing single session data, it was found that both fatigue and exertion increased from pre-session to post-session.[13]

In contrast, other studies examined exertion over the whole intervention period and showed that using an exoskeleton required less exertion overtime. An eight subject SCI Ekso study showed a decrease in effort (demonstrated by Borg scores) required to use the device throughout the study which they concluded was an amelioration of gait ability and performance.[14] Another 52 subjects who utilized Ekso reported a significant decrease in RPE scores (i.e. less exertion) over the course of the study and the authors concluded that these results indicate that it isn't overly taxing to use the device, therefore it can be used by individuals with SCI for longer periods of time.[15] A third Ekso study in 3 SCI subjects showed a decrease in both Borg RPE scores (i.e. less exertion) and VAS Fatigue scores by the end of the study.[16] A 4 subject SCI ReWalk study demonstrated a decrease in Energy Expenditure in using the device over the course of the study[17] and another SCI ReWalk study noted that only 1 out of 11 subjects reported that using ReWalk caused fatigue.[18] Borg scale scores (rated on a scale of 6-20) decreased from an average of 15 (hard (heavy)) to 11 (light) for eleven subjects in a 12 session ABLE exoskeleton SCI study.[19] A 45 subject SCI study with the Indego device reported a significant decrease in Borg RPE scores (rated on a scale of 6-20) for indoor walking from 11.7±2.1 at the beginning of the study to 10.4±2.2 at the end of the study indicating that less exertion was required to use the device by the end of the study.[20] In a single subject case study comparing the Indego exoskeleton to long leg braces, it was found that the subject was able to walk faster with less exertion in the Indego.[21] A 10 subject ReWalk study that compared the exoskeleton to KAFOs reported that the ReWalk had a higher energy efficiency.[22] These results indicate that with practice, using an exoskeleton becomes easier, and comparatively is easier than bracing, which together could make a case for the use of home exoskeletons.

While most of the research agrees that exoskeletons can be used for exercise and that longer term use of the device causes the body to acclimate to this exercise, some research opposes this. In a case study for an individual with SCI using the UAN.GO device, it was found that Borg RPE scores remained consistent as it was measured at the end of each 6 minute walk test throughout the study.[23] However, it was also noted that the individual reported fatigue due to upper limb overload while using the device.[24] A randomized SCI study that compared Lokomat to Ekso in 5 subjects found minimal or no change in RPE for all participants with the exception of one Ekso subject whose RPE scores increased slightly (i.e. more exertion was required) from the beginning to the end of the study.[23] A study looking at Phoenix demonstrated that when evaluating the data from entirety of the study, both fatigue and exertion appeared to increase then decrease slightly and then increase again slightly.[13]

A couple of review articles focus on persons with SCI. One review looking specifically at individuals with SCI using various devices (ReWalk, Ekso, Lokomat, and others) concluded that walking in an exoskeleton does not improve energy expenditure compared to other exercise.[25] Another review focusing on persons with SCI offered an explanation for the wide range of reported Borg RPE scores; dosage and exposure to the device may influence Borg RPE scores as newness of a device may yield higher Borg RPE scores (i.e more exertion).[26] The authors also concluded that most studies generally report a decrease in effort and fatigue after using an exoskeleton.[26]

Stroke (CVA)

There are a few articles that examine exertion in persons post CVA and they largely disagree. A fourteen subject study utilizing several different devices reported an average category-ratio Borg score of 4 (rated on a scale of 0-10) which correlates to “somewhat severe” exertion and thus fairly high intensity exercise.[27] In contrast, a twenty-six subject Ekso study in persons with CVA noted that users experienced “light” exertion while using the device, which the authors conclude indicates that the Ekso is less tiring than overground walking and feasible to use in persons with severe functional deficits in therapy.[28] Another Ekso study that compared able-bodied individuals to those with CVA concluded that the physical training intensity associated with device usage may not be high enough, however, this could also lead one to infer that the device is easy to use which is also important.[29]

Multiple Sclerosis (MS)

Fatigue and exertion are very important outcome to examine in persons with MS due to the nature of the disease. A 36 subject study in persons with Multiple Sclerosis compared Ekso use to conventional therapy and found that individuals in the Ekso group maintained their 10 meter walk test (10MWT) speeds in addition to improving their TUG test scores without increasing fatigue as measured by the Modified Fatigue Impact Scale.[30] The conventional therapy group had slower 10MWT times and reduced fatigue.[30] A single subject MS case study using the Ekso reported a decrease in the shortened Modified Fatigue Impact Scale (sMFIS) from 11 at baseline to 10 post-Ekso therapy, where scores range from 0-20 with higher numbers indicating greater fatigue.[31] The Fatigue Severity Scale (FSS), which rates fatigue on a scale of 1-7 where higher scores indicate greater fatigue, was used to assess fatigability in 14 persons with Multiple Sclerosis in an Ekso study.[32] This study reported FSS scores of 5.01 at the start of the study, 4.89 at the end of the therapy portion without the device, and 4.37 at the end of the Ekso training part of the study.[32] A single subject case study where an individual with Multiple Sclerosis used the Ekso noted a decrease in fatigue from 11 at the start of the study to 10 at the end of the study, as measured by the shortened Modified Fatigue Impact Scale (sMFIS) on a scale of 0-20 where higher scores indicates greater fatigue.[31] Borg RPE scores decreased from 15 (hard (heavy)) at the beginning of the study to 11 (fairly light) at the end of the study in a single subject with MS who utilized the UAN.GO device.[33] A review article examining the effect of various robotic and exoskeleton gait training devices in individuals with MS concluded that these devices did not appear to have an adverse effects on fatigue.[34] Another Ekso study in 10 persons with MS reported Borg RPE scores ranging from 9 (very light) to 15 (hard(heavy)) which indicated that the training was overall not intensive.[35] A 54 subject Ekso study in individuals with Multiple Sclerosis reported an average Modified Fatigue Impact Scale (MFIS) score of 42.38 (rated on a scale of 0-84 where greater numbers indicate greater fatigue)[36] compared to a baseline MFIS score of 33 for persons with Multiple Sclerosis at rest as reported by Téllez et al, 2005.[37]

Review Articles

One review article compared individuals with SCI and CVA to able-bodied persons using a wide variety of devices from treadmill based devices (Lokomat) to exoskeletons and ankle exoskeletons determined that, in general, robotic walking required less energy than overground walking.[38]

Conclusions

The literature regarding exertion with exoskeleton usage in individuals with various diagnoses resulting in lower limb weakness is inconclusive. Some studies report low exertion, which may be beneficial for those using their devices in their homes and communities, while other studies report higher exertion, which may be desirable for those wishing to use the device as a form of exercise. It is important to note that very few of these studies specify the software configuration that the exoskeleton was used in, which could significantly alter how much work the subject is completing. For example, a lower Borg RPE score (i.e. less exertion) would be expected for a participant who has the exoskeleton device set to provide them full assistance, as opposed to the expectation of a higher Borg RPE score (i.e. more exertion) when removing some or all of the robotic assistance of the exoskeleton which would require the participant to work harder.

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All known articles assessing exertion in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
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 systematic review of the effects of robotic exoskeleton training on energy expenditure and body composition in adults with spinal cord injury	Rigoli A, Francis L, Nicholson M, Weber G, Redhead J, Iyer P	Int J Rehabil Res. 2024 Jun 1;47(2):64-74.	ReWalk, Ekso, Lokomat	SCI
Exoskeletal-Assisted Walking During Acute Inpatient Rehabilitation Enhances Recovery for Persons with Spinal Cord Injury – A Pilot Randomized Controlled Trial	Tsai C-Y, Weinrauch WJ, Manente N, Huang V, Bryce TN, Spungen AM	J Neurotrauma. 2024 May 8.	Ekso	SCI
Robotic assisted and exoskeleton gait training effect in mental health and fatigue of multiple sclerosis patients. A systematic review and a meta-analysis	Christodoulou VN, Varvarousis DN, Ntritsos G, Dimopoulos D, Giannakeas N, Vasileiadis GI, Korompilias A, Ploumis A	Disabil Rehabil. 2024 Apr 14:1-12.	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 standardization of clinical evaluations	Wright MA, Herzog F, Mas-Vinyals A, Carnicero-Carmona A, Lobo-Prat J, Hensel C, Franz S, Weidner N, Vidal J, Opisso E, Rupp R	J Neuroeng Rehabil. 2023 Apr 12;20(1):45.	Able	SCI
Feasibility and cost description of highly intensive rehabilitation involving new technologies in patients with post-acute stroke – a trial of the Swiss RehabTech Initiative	Schuster-Amft C, Kool J, Möller C, Schweinfurther R, Ernst MJ, Reicherzer L, Ziller C, Schwab ME, Wieser S, Wirz M, and for the SRTI study group	Pilot Feasibility Stud. 2022 Jul 5;8(1):139.	Multiple	CVA
Rehabilitation Program for Gait Training Using UAN.GO, a Powered Exoskeleton: A Case Report	Lamberti G, Sesenna G, Paja Q, Ciardi G	Neurol Int. 2022 Jun 16;14(2):536-546.	UAN.GO	SCI
Implementing the exoskeleton Ekso GTtm for gait rehabilitation in a stroke unit – feasibility, functional benefits and patient experiences	Høyer E, Opheim A, Jørgensen V	Disabil Rehabil Assist Technol. 2022 May;17(4):473-479.	Ekso	CVA

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Knowledge Gaps in Biophysical Changes After Powered Robotic Exoskeleton Walking by Individuals With Spinal Cord Injury – A Scoping Review	Yip CCH, Lam C-Y, Cheung KMC, Wong YW, Koljonen PA	Front Neurol. 2022 Mar 10;13:792295.	Multiple – Review Article	SCI
Walking with UAN.GO Exoskeleton: Training and Compliance in a Multiple Sclerosis Patient	Sesenna G, Calzolari C, Gruppi MP, Ciardi G	Neurol Int. 2021 Aug 23;13(3):428-438	UAN.GO	MS
Exoskeleton gait training to improve lower urinary tract function in people with motor-complete spinal cord injury: A randomized pilot trial	Williams AMM, Deegan E, Walter M, Stothers L, Lam T	J Rehabil Med. 2021 Aug 26;53(8):jrm00222.	Ekso, Lokomat	SCI
Wearable Robotic Gait Training in Persons with Multiple Sclerosis: A Satisfaction Study	Fernández-Vázquez D, Cano-de-la-Cuerda R, Gor-García-Fogeda MD, Molina-Rueda F	Sensors (Basel). 2021 Jul 20;21(14):4940.	Ekso	MS
Outcomes of a Multicenter Safety and Efficacy Study of the SuitX Phoenix Powered Exoskeleton for Ambulation by Patients With Spinal Cord Injury	Koljonen PA, Virk AS, Jeong Y, McKinley M, Latorre J, Caballero A, Hu Y, Wong YW, Cheung K, Kazerooni H	Front Neurol. 2021 Jul 19;12:689751.	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 J-L, Francisco GE, Chang S-H	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	Berriozabalgoitia R, Bidaurrazaga-Letona I, Otxoa E, Urquiza M, Irazusta J, Rodriguez-Larrad A	Arch Phys Med Rehabil. 2021 May;102(5):932-939.	Ekso	MS
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

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Wearable exoskeleton control modes selected during overground walking affect muscle synergies in adults with a chronic incomplete spinal cord injury	Escalona MJ, Bourbonnais D, Goyette M, Duclos C, Gagnon DH	Spinal Cord Ser Cases. 2020 Apr 24;6(1):26.	Ekso	SCI
Energy Efficiency and Patient Satisfaction of Gait With Knee-Ankle-Foot Orthosis and Robot (ReWalk) – Assisted Gait in Patients With Spinal Cord Injury	Kwon SH, Lee BS, Lee HJ, Kim EJ, Lee JA, Yang SP, Kim TY, Pak HR, Kim HK, Kim HY, Jung JH, Oh SW	Ann Rehabil Med. 2020 Apr;44(2):131-141.	ReWalk	SCI
Exoskeleton-assisted Gait Training in Persons With Multiple Sclerosis: A Single-Group Pilot Study	Afzal T, Tseng S-C, Lincoln JA, Kern M, Francisco GE, Chang S-H	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 After Spinal Cord Injury	McIntosh K, Charbonneau R, Bensaada Y, Bhatiya U, Ho C	Arch Phys Med Rehabil. 2020 Jan;101(1):113-120.	Ekso	SCI
Acute Metabolic and Glycemic Responses to Bionic Ambulation in Spinal Cord Injured Humans and Controls	Maher JL, Baunsgaard CB, van Gerven J, Palermo AE, Biering-Sorensen F, Mendez A, Irwin RW, Nash MS	Arch Phys Med Rehabil. 2020 Jan;101(1):121-129.	Ekso	SCI, able-bodied
Cardiometabolic Challenges Provided by Variable Assisted Exoskeleton 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
Training for mobility with exoskeleton robot in Person with Spinal Cord Injury: A pilot study	Sale P, Russo EF, Masiero S, Scarton A, Calabrò, Filoni S	Eur J Phys Rehabil Med. 2018 Oct;54(5):745-751.	Ekso	SCI
Examining the Effects of a Powered Exoskeleton on Quality of Life and Secondary Impairments in People Living with Spinal Cord Injury	Juszczak M, Gallo E, Bushnik T	Top Spinal Cord Inj Rehabil. 2018 Fall;24(4):336-342.	Indego	SCI

All known articles assessing exertion in participants using an exoskeleton

Title	Authors	Journal	Device	Diagnosis
Cardiorespiratory demand and rate of perceived exertion during overground walking with a robotic exoskeleton in long-term manual wheelchair users with chronic spinal cord injury: A cross-sectional study	Escalona MJ, Brosseau R, Vermette M, Comtois AS, Duclos C, Aubertin-Leheudre M, Gagnon DH	Ann Phys Rehabil Med. 2018 Jul;61(4):215-223.	Ekso	SCI
Respiratory, cardiovascular and metabolic responses during different modes of overground bionic ambulation in persons with motor-incomplete spinal cord injury: A case series	Kressler J, Wymer T, Domingo A	J Rehabil Med. 2018 Feb 13;50(2):173-180.	Ekso	SCI
Gait training after spinal cord injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics	Baunsgaard CB, Nissen UV, Brust AK, Frotzler A, Ribeill C, Kalke Y-B, 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
The immediate effects of robot-assistance on energy consumption and cardiorespiratory load during walking compared to walking without robot-assistance: a systematic review	Lefeber N, Swinnen E, Kerckhofs E	Disabil Rehabil Assist Technol. 2017 Oct;12(7):657-671.	Multiple – Review Article	SCI, CVA, able-bodied
Accelerometry-enabled measurement of walking performance with a robotic exoskeleton: a pilot study	Lonini L, Shawen N, Scanlan K, Rymer WZ, Kording KP, Jayaraman A	J Neuroeng Rehabil. 2016 Mar 31;13:35.	ReWalk	SCI
Lower-limb exoskeletons for individuals with chronic spinal cord injury: Findings from a feasibility study	Benson I, Hart K, Tussler D, van Middendorp JJ	Clin Rehabil. 2016 Jan;30(1):73-84.	ReWalk	SCI
Time and Effort Required by Persons with Spinal Cord Injury to Learn to Use a Powered Exoskeleton for Assisted Walking	Kozlowski AJ, Bryce TN, Dijkers MP	Top Spinal Cord Inj Rehabil. 2015 Spring;21(2):110-21.	Ekso	SCI

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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 ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study	Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A	J Spinal Cord Med. 2012 Mar;35(2):96-101.	ReWalk	SCI

CVA = stroke, MS = multiple sclerosis, SCI = spinal cord injury