**Cardiovascular Effects**

There are many articles in the literature that evaluate the use of robotic exoskeletons and their effect on cardiovascular outcome measures across a variety of diagnoses. Most of these publications cover the Ekso 1.1/GT/NR device (25), referred to as “Ekso” in this paper. Other devices used include ReWalk (9), Indego (6), HAL (5), ExoAtlet (2), and SuitX Phoenix (1), among others. The most widely studied diagnosis was Spinal Cord Injury (23), followed by CVA (1) and ABI (1). The most commonly reported outcome measures in regard to cardiovascular effects were Heart Rate (HR) (26), Blood Pressure (BP) (16), VO2 (15) and VCO2 (4).

*Spinal Cord Injury (SCI)*

Several articles in the literature demonstrated that robotic exoskeleton usage in persons with SCI can induce positive cardiovascular effects and even exercise. In a 13 subject Ekso study in participants with SCI, it was found that cardiorespiratory measures including peak heart rate and oxygen uptake (HRpeak and VO2peak) increased from 9-35% from sitting to standing and further by 22-52% from standing to walking with the Ekso in a single session.1 The authors concluded that walking in the Ekso allowed these users to achieve moderate intensity levels of exercise.1 Walking was found to induce a higher average VO2 when compared to either sitting or standing in both individuals with SCI and healthy controls in another Ekso study.2 An 8 subject ReWalk study in persons with SCI reported that average oxygen uptake and heart rate were found to be significantly higher for walking when compared to sitting or standing.3 One participant from a four subject Ekso SCI study demonstrated an increase in oxygen uptake from 0.27 L/min during rest to 0.55 L/min during walking.4 Another 4 subject Ekso study in persons with SCI reported a range of cardiorespiratory responses from low (24% VO2peak) in the least impaired individual to supramaximal (124% VO2peak) in the participant with the greatest impairment.5 A smaller two subject Ekso SCI case study reported similar findings; exoskeleton walking was compared to overground walking without a device and it was found that the participant with a lower starting walking capacity had greater cardiorespiratory responses than the participant that started with a greater walking capacity.6 An Indego study in persons with SCI that evaluated cardiorespiratory and metabolic responses at different walking speeds found that walking in the device resulted in %VO2peak range of 51.5 to 63.2% and metabolic cost ranged from 3.5 to 4.3 METsSCI.7 Participants in an Ekso SCI study were able to achieve light to moderate levels of exercise based on reported heart rate changes.8 A case study using a subject who ambulated with the Ekso found an increase in both heart rate and blood pressure when active voluntary effort was required (i.e. less device assistance).9 A 52 subject multisite Ekso study in persons with SCI who completed a median of 21 sessions reported a significant increase in heart rate during the sessions and no change in blood pressure.10 Data analysis in an 11 subject SCI Ekso study where participants used the device three times per week for up to 25 sessions revealed no significant differences over time for heart rate or blood pressure when looking at the study from beginning to end however, heart rate did increase 15-21% within the sessions while blood pressure remained unchanged.11 Another single subject SCI case study found that walking in the Ekso in combination with spinal stimulation yielded an increase in cardiac response as measured by heart rate and blood pressure.12 Two ReWalk SCI studies reported that average heart rate and blood pressure were found to be higher following a training session.13,14 A third ReWalk study in six persons with SCI noted that average blood pressure went from 121/77 pre-session to 129/83 post-session and average heart rate went from 68 pre-session to 92 post-session, indicating an exercise-like response.15Although inconsistency in VO2 measures was reported in a 3 subject SCI Ekso study, elevated heart rates were found in all participants when compared to seated rest.16 In an SCI case study with 2 subjects it was found that the subjects reached peak HR at 53% and 60% of age predicted max after a single session with the Ekso.17 Fifteen individuals with SCI used both Ekso and Lokomat and it was found that greater cardiovascular effort was required when using the Ekso.18 A review of various devices found that gait training with robotic assistance improved peak oxygen consumption to a greater degree for subjects with chronic incomplete spinal cord injury.19 Several of these studies reported significant increases in heart rate after using an exoskeleton in persons with SCI and some noted that users were able to achieve light to moderate levels of exercise.

Other studies focused on the evidence showing that exoskeletons were not overly taxing to use in regard to cardiovascular effects. One eight subject SCI Ekso study found no effects on VO2 after using the device two to three times per week for 12 weeks.20 A ReWalk study in persons with SCI compared the device to a KAFO and found higher VO2 and VO2max values for the KAFO in both the six minute walk test (6MWT) and 30 minute walk test (30MWT).21 In a randomized 16 subject SCI study that compared Ekso to activity based therapy, it was found that the standing heart rate was significantly higher in the activity group when compared to the Ekso group at the end of the study.22 However, it was noted in the same study that cardiovascular efficiency improved during the 6MWT for the Ekso group after 6 weeks and was maintained though the end of the 24 week study period.22 These publications indicated that exoskeletons were no harder, and even easier in some cases, to use when compared to alternative therapies like KAFOs or activity based therapy.

Another interesting study in 12 non-randomized SCI participants compared Ekso with usual care physiotherapy and found a significant reduction in arterial wave reflection and mean arterial pressure which is notable because arterial wave reflection, which can be used to infer the degree of systemic arterial wave reflection, has been shown to predict future cardiovascular events and all-cause mortality independent of blood pressure.23 Arterial wave reflection is the augmentation pressure expressed as a percentage of central pulse pressure.23

*Stroke (CVA)*

The literature reporting on cardiovascular effects in persons with CVA who utilized a robotic exoskeleton is slim. A two subject Ekso study in persons with CVA found that the participants achieved 75-85% of the calculated max heart rates through 86-100% of the 30 training sessions, completed over a period of 10 weeks.24

*Acquired Brain Injury (ABI)*

There is only one known publication evaluating the cardiovascular effect of robotic exoskeletons in persons with ABI. Ten subjects with ABI used the Ekso and it was reported that participants were in the light to very light range for HR during the 10.4 ± 4.8 completed sessions.25

*Review Articles*

One review examining both body weight supported treadmills (BWSTT) and overground exoskeletons concluded that walking in an exoskeleton led to improvements in cardiovascular endurance while BWSTT did not.26 A review that examined studies using various devices (including gait trainer, Lokomat, Indego, HAL, and SMA, among others) in persons with CVA, SCI, and healthy subjects concluded that metabolic and cardiorespiratory outcome measures were lower during robot assisted gait when compared to walking without a device.27 Another review that examined 31 articles using various devices in persons with SCI came to the conclusion that the use of such a wide range of metrics to measure cardiovascular outcomes made these studies too difficult to compare.28 Use of several different devices in persons with SCI was evaluated in another review and while the authors acknowledged that significant increases in HR and oxygen consumption while transitioning from sitting to standing were reported in several different studies, they offered the explanation that this may be considered a normal response to maintaining blood pressure when changing position.29

*Conclusions*

As mentioned in a review article28 above, the wide variety of outcome measures reported in the literature make it challenging to draw an overall conclusion on the cardiovascular effect of robotic exoskeletons. In general, using the devices led to increases in outcome measures such as heart rate, blood pressure, and VO2. Although these results did not necessarily correlate to high intensity exercise, these increases were seen as positive.

**References**

1. Escalona MJ, Brosseau R, Vermette M, et al. 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. *Ann Phys Rehabil Med*. 2018;61(4):215-223. doi:10.1016/j.rehab.2017.12.008

2. Maher JL, Baunsgaard CB, Van Gerven J, et al. Differences in Acute Metabolic Responses to Bionic and Nonbionic Ambulation in Spinal Cord Injured Humans and Controls. *Arch Phys Med Rehabil*. 2020;101(1):121-129. doi:10.1016/j.apmr.2019.07.014

3. Asselin P, Knezevic S, Kornfeld S, et al. Heart rate and oxygen demand of powered exoskeleton-assisted walking in persons with paraplegia. *J Rehabil Res Dev*. 2015;52(2):147-158. doi:10.1682/JRRD.2014.02.0060

4. Gorgey AS, Wade R, Sumrell R, Villadelgado L, Khalil RE, Lavis T. Exoskeleton Training May Improve Level of Physical Activity After Spinal Cord Injury: A Case Series. *Top Spinal Cord Inj Rehabil*. 2017;23(3):245-255. doi:10.1310/sci16-00025

5. Kressler J, Wymer T, Domingo A. Respiratory, cardiovascular and metabolic responses during different modes of overground bionic ambulation in persons with motor-incomplete spinal cord injury: A case series. *J Rehabil Med*. 2018;50(2):173-180. doi:10.2340/16501977-2281

6. Kressler J, Domingo A. Cardiometabolic Challenges Provided by Variable Assisted Exoskeletal Versus Overground Walking in Chronic Motor-incomplete Paraplegia: A Case Series. *J Neurol Phys Ther*. 2019;43(2):128-135. doi:10.1097/NPT.0000000000000262

7. Evans N, Hartigan C, Kandilakis C, Pharo E, Clesson I. Acute Cardiorespiratory and Metabolic Responses During Exoskeleton-Assisted Walking Overground Among Persons with Chronic Spinal Cord Injury. *Top Spinal Cord Inj Rehabil*. 2015;21(2):122-132. doi:10.1310/sci2102-122

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

9. Gad P, Gerasimenko Y, Zdunowski S, et al. Weight Bearing Over-ground Stepping in an Exoskeleton with Non-invasive Spinal Cord Neuromodulation after Motor Complete Paraplegia. *Front Neurosci*. 2017;11:333. doi:10.3389/fnins.2017.00333

10. 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

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

12. Gad PN, Gerasimenko YP, Zdunowski S, et al. Iron ‘ElectriRx’ man: Overground stepping in an exoskeleton combined with noninvasive spinal cord stimulation after paralysis. In: *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE; 2015:1124-1127. doi:10.1109/EMBC.2015.7318563

13. 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

14. Esquenazi A, Talaty M, Packel A, Saulino M. The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. *Am J Phys Med Rehabil*. 2012;91(11):911-921. doi:10.1097/PHM.0b013e318269d9a3

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

16. Kressler J, Thomas CK, Field-Fote EC, et al. Understanding Therapeutic Benefits of Overground Bionic Ambulation: Exploratory Case Series in Persons With Chronic, Complete Spinal Cord Injury. *Arch Phys Med Rehabil*. 2014;95(10):1878-1887.e4. doi:10.1016/j.apmr.2014.04.026

17. Bosteder KD, Moore A, Weeks A, et al. Intensity of overground robotic exoskeleton training in two persons with motor-complete tetraplegia: a case series. *Spinal Cord Ser Cases*. 2023;9(1):24. doi:10.1038/s41394-023-00584-4

18. Corbianco S, Cavallini G, Dini M, et al. Energy cost and psychological impact of robotic-assisted gait training in people with spinal cord injury: effect of two different types of devices. *Neurol Sci*. 2021;42(8):3357-3366. doi:10.1007/s10072-020-04954-w

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

20. Sutor TW, Ghatas MP, Goetz LL, Lavis TD, Gorgey AS. Exoskeleton Training and Trans-Spinal Stimulation for Physical Activity Enhancement After Spinal Cord Injury (EXTra-SCI): An Exploratory Study. *Front Rehabil Sci*. 2022;2:789422. doi:10.3389/fresc.2021.789422

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

22. Evans RW, Shackleton CL, West S, et al. Robotic Locomotor Training Leads to Cardiovascular Changes in Individuals With Incomplete Spinal Cord Injury Over a 24-Week Rehabilitation Period: A Randomized Controlled Pilot Study. *Arch Phys Med Rehabil*. 2021;102(8):1447-1456. doi:10.1016/j.apmr.2021.03.018

23. Faulkner J, Martinelli L, Cook K, et al. Effects of robotic-assisted gait training on the central vascular health of individuals with spinal cord injury: A pilot study. *J Spinal Cord Med*. 2021;44(2):299-305. doi:10.1080/10790268.2019.1656849

24. Nolan KJ, Ames GR, Dandola CM, et al. Intensity Modulated Exoskeleton Gait Training Post Stroke. *Annu Int Conf IEEE Eng Med Biol Soc IEEE Eng Med Biol Soc Annu Int Conf*. 2023;2023:1-4. doi:10.1109/EMBC40787.2023.10340452

25. Gillespie J, Trammell M, Ochoa C, et al. Feasibility of overground exoskeleton gait training during inpatient rehabilitation after severe acquired brain injury. *Brain Inj*. Published online February 18, 2024:1-8. doi:10.1080/02699052.2024.2317259

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

27. Lefeber N, Swinnen E, Kerckhofs E. The immediate effects of robot-assistance on energy consumption and cardiorespiratory load during walking compared to walking without robot-assistance: a systematic review. *Disabil Rehabil Assist Technol*. 2017;12(7):657-671. doi:10.1080/17483107.2016.1235620

28. Yip CCH, Lam CY, Cheung KMC, Wong YW, Koljonen PA. Knowledge Gaps in Biophysical Changes After Powered Robotic Exoskeleton Walking by Individuals With Spinal Cord Injury—A Scoping Review. *Front Neurol*. 2022;13:792295. doi:10.3389/fneur.2022.792295

29. Tamburella F, Lorusso M, Tramontano M, Fadlun S, Masciullo M, Scivoletto G. Overground robotic training effects on walking and secondary health conditions in individuals with spinal cord injury: systematic review. *J NeuroEngineering Rehabil*. 2022;19(1):27. doi:10.1186/s12984-022-01003-9

| **Title** | **Authors** | **Journal** | **Device** | **Diagnosis** |
| --- | --- | --- | --- | --- |
| Feasibility of overground exoskeleton gait training during inpatient rehabilitation after severe acquired brain injury | Gillespie J, Trammell M, Ochoa C, Driver S, Callender L, Dubiel R, Swank C | Brain Inj. 2024 May 11;38(6):459-466. | Ekso | ABI |
| 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 |
| Intensity of overground robotic exoskeleton training in two persons with motor-complete tetraplegia: a case series | Bosteder KD, Moore A, Weeks A, Dawkins JD, Trammell M, Driver S, Hamilton R, Swank C | Spinal Cord Ser Cases. 2023 Jul 1;9(1):24. | Ekso | SCI |
| Effectiveness of robotic-assisted gait training on cardiopulmonary fitness and exercise capacity for incomplete spinal cord injury: A systematic review and meta-analysis of randomized controlled trials | Li R, Ding M, Wang J, Pan H, Sun X, Huang L, Fu C, He C, Wei Q. | Clin Rehabil. 2023 Mar;37(3):312-329. | Multiple – Review Article | SCI |
| 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 |
| 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, Picelli A, Senatore M, Turchetti G, Bizzarrini E | NeuroRehabilitation. 2022;51(4):609-647. | Multiple – Review Article | SCI |
| Knowledge Gaps in Biophysical Changes After Powered Robotic Exoskeleton Walking by Individuals With Spinal Cord Injury-A Scoping Review | Yip CCH, Lam CY, Cheung KMC, Wong YW, Koljonen PA | Front Neurol. 2022 Mar 10;13:792295. | Multiple – Review Article | SCI |
| Overground robotic training effects on walking and secondary health conditions in individuals with spinal cord injury: systematic review | Tamburella F, Lorusso M, Tramontano M, Fadlun S, Masciullo M, Scivoletto G | J Neuroeng Rehabil. 2022 Mar 15;19(1):27. | Multiple – Review Article | SCI |
| Exoskeleton Training and Trans-Spinal Stimulation for Physical Activity Enhancement After Spinal Cord Injury (EXTra-SCI): An Exploratory Study | Sutor TW, Ghatas MP, Goetz LL, Lavis TD, Gorgey AS | Front Rehabil Sci. 2022 Jan;2:789422. | Ekso | SCI |
| Robotic locomotor training leads to cardiovascular changes in individuals with incomplete spinal cord injury over a 24-week rehabilitation period: a randomized controlled pilot study | Evans RW, Shackleton C, West S, Derman W, Laurie Rauch HG, Baalbergen E, Albertus Y | Arch Phys Med Rehabil. 2021 Aug;102(8):1447-1456. | Ekso | SCI |
| Energy cost and psychological impact of robot-assisted gait training in people with spinal cord injury: effect of two types of devices | Corbianco S, Cavallini G, Dini M, Franzoni F, D’Avino C, Gerini A, Stampacchia G | Neurol Sci. 2021 Aug;42(8):3357-3366. | Ekso | SCI |
| Effects of robotic-assisted gait training on the central vascular health of individuals with spinal cord injury: A pilot study | Faulkner J, Martinelli L, Cook K, Stoner L, Ryan-Stewart H, Paine E, Hobbs H, Lambrick D | J Spinal Cord Med. 2021 Mar;44(2):299-305. | Ekso | SCI |
| Energy Efficiency and Patient Satisfaction of Gait With Knee-Ankle-Foot Orthosis and Robot (ReWalk)-Assisted 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 |
| 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 |
| Differences in Acute Metabolic Responses to Bionics and Nonbionic 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 |
| 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 |
| 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-complete 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 | Bach Baunsgaard C, Vig Nissen U, Katrin Brust A, Frotzler A, Ribeill C, Kalke TB, 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 |
| Exoskeleton Training May Improve Level of Physical Activity After Spinal Cord Injury: A Case Series | Gorgey AS, Wade R, Sumrell R, Villadelgado L, Khalil RE, Lavis T. | Top Spinal Cord Inj Rehabil. 2017 Summer;23(3):245-255. | Ekso | SCI |
| Weight Bearing Over-ground Stepping in an Exoskeleton with Non-invasive Spinal Cord Neuromodulation after Motor Complete Paraplegia | Gad P, Gerasimenko Y, Zdunowski S, Turner A, Sayenko D, Lu DC, Edgerton VR | Front Neurosci. 2017 Jun 8;11:333. | Ekso | 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 |
| Heart rate and oxygen demand of powered exoskeleton-assisted walking in persons with paraplegia | Asselin P, Knezevic S, Kornfeld S, Cirnigliaro C, Agranova-Breyter I, Bauman WA, Spungen AM | J Rehabil Res Dev. 2015;52(2):147-58. | ReWalk | SCI |
| Iron ‘ElectriRx’ man: Overground stepping in an exoskeleton combined with noninvasive spinal cord stimulation after paralysis | Gad PN, Gerasimenko YP, Zdunowski S, Sayenko D, Haakana P, Turner A, Lu D, Roy RR, Edgerton VR | Annu Int Conf IEEE Eng Med Biol Soc. 2015 Aug;2015:1124-7. | Ekso | 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 |
| 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. | Ekso | SCI |
| Safety and Feasibility of the Using the EksoTM Bionic Exoskeleton to Aid Ambulation after Spinal Cord Injury | Kolakowsky-Hayner SA, Crew J, Moran S, Shah A. | J Spine. 2013 | Ekso | 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 |

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