Clinician-Focused Overview of Bionic Exoskeleton Use After Spinal Cord Injury

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Spinal cord injury (SCI) resulting in paralysis of lower limbs and trunk restricts daily upright activity, work capacity, and ambulation ability, putting persons with an injury at greater risk of developing a myriad of secondary medical issues. Time spent in the upright posture has been shown to decrease the risk of these complications in SCI. Unfortunately, the majority of ambulation assistive technologies are limited by inefficiencies such as high energy demand, lengthy donning and doffing time, and poor gait pattern precluding widespread use. These limitations spurred the development of bionic exoskeletons. These devices are currently being used in rehabilitation settings for gait retraining, and some have been approved for home use. This overview will address the current state of available devices and their utility. **Key words:** bionic ambulation, community ambulation, Ekso, exoskeleton, gait retraining, Indego, ReWalk, spinal cord injury

Spinal cord injury (SCI) resulting in paralysis of the lower limbs and trunk is known to restrict daily activity in the upright position, diminish levels of fitness and work capacity,¹ and promote an accelerated trajectory of secondary medical complications including central obesity, dyslipidemia, and dysglycemia.² More than half of persons sustaining spinal cord damage have incomplete motor lesions (iSCI),³ leaving spared neural pathways capable of limited somatic motor function.⁴ Prognosis for recovery of lower limb function and eventual walking varies depending on factors such as the level and completeness of the injury. The more incomplete the injury, the more favorable the potential for ambulation recovery.⁵⁻⁷ Additional factors to consider are the individual's age at injury,⁸ rehabilitation training received, motivation, and socioeconomic status.⁹

A wide range of responses is obtained from stakeholders with SCI when rank ordering their desire to recover greater functional independence after injury. A 2004 survey conducted by Anderson¹⁰ reported that regaining walking movement was cited as the highest priority by only 7.8% and 15.9% of individuals with paraplegia and tetraplegia, respectively. Of higher

importance were arm/hand function in persons with tetraplegia, sexual function in people with paraplegia, and improved bladder/bowel function and elimination of autonomic dysreflexia in both groups. More recently Ditunno et al¹¹ reported that most consumer panels surveyed expressed a preference for the restoration of walking function over most other functions on the modified Functional Independence Measure (mFIM). This observation suggests a need for a greater emphasis on treatment and research activities that focus on the restoration of walking.

Assistive Technology for Ambulation

Time spent in the upright position after SCI has been reported to lessen the risk of lower extremity joint contractures, osteoporosis, spasticity, bed sores, and edema.^{6,12} Additional benefits are experienced when this regimen is adopted as an early intervention strategy following injury.^{6,12} Leg braces and orthoses were first developed to support standing and walking; these varied from single-joint braces (eg, ankle-foot orthoses) for individuals with low or incomplete spinal lesions to long-leg braces that extend across the ankle and

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knee to the upper thigh. The function of these braces was improved through the incorporation of pelvic and thoracic extensions and reciprocating actions of the hip joints that were achieved by an isocentric bar or cables linking flexion and extension actions of the hip joints. Hybrid systems then incorporated functional electrical stimulation (FES) to provide postural stability along with muscle activation for persons with complete or weak incomplete injuries. However, the extent to which these devices created more efficient and natural gait was limited, and all required use of a walking aid, such as crutches or a walker, to sustain functional ambulation. Overall, inefficiencies such as high energy demand, lengthy donning and doffing time,¹³ and poor gait pattern¹⁴ limited the long-term use of these ambulatory systems¹⁵ as an alternate to the wheelchair.

Bionic exoskeletons are among the emerging rehabilitation modalities that claim to provide functional ambulation, reduce medical complications accompanying SCI, and stimulate plasticity of motor pathways after iSCI.¹⁶ As derivatives of military applications, motorized exoskeletons support ambulation by assisting or completely moving the legs of the user in a reciprocal stepping pattern without the need for tethering, which offers the opportunity to walk at home and in the community. In general, bionic movements are programmed to mimic a more natural gait pattern than what is achievable with long-leg braces and reciprocating gait orthoses. Unlike earlier braces that required user-generated power to initiate stepping, bionic exoskeletons have onboard motors that initiate and sequence the stepping motion. Some devices used in gait retraining of individuals with iSCI provide an adjustable amount of assistance based on the spared motor function of the user. They can be used as an alternative to body weight-supported treadmill training (BWSTT) or robotic-assisted gait training (RAGT; Lokomat [Hocoma, Switzerland] and similar devices) on stationary treadmills. Additionally, selected exoskeletons have received US Food and Drug Administration (FDA) approval as mobility devices for functional ambulation in the home and community setting. An overview of FDA-approved devices and general device information is shown in **Table 1**. Two

other manufacturers with current CE Marking (European market) may qualify for FDA approval shortly; these include the Japan-based company Cyberdyne with its Hybrid Assistive Limb (HAL) and the New Zealand-based company REX Bionics with its exoskeletons REX Rehab and REX P, custom fitted for personal use.

Guidelines and Use of Bionic Exoskeletons

Manufacturer-determined guidelines

To ensure user safety, inclusion and exclusion criteria have been adopted for the majority of marketed exoskeletons (**Table 1**). Manufacturer guidelines vary by device but have relatively consistent recommendations for use by injury level, completeness of injury, and the ability to safely use an assistive device such as a walker or forearm crutches. Manufacturers and previous studies describe fairly consistent contraindications among exoskeletons (**Table 2**). The most restrictive height range is imposed by the Phoenix (SuitX; **Figure 1**),¹⁷ and the most restrictive body mass is the Wearable Power-Assist Locomotor (WPAL).¹⁸ The widest ranges of body and injury characteristics are accommodated by the Axosuit (Axosuits SRL) exoskeleton.¹⁹

In addition to body characteristics, other factors may limit an individual's ability to use an exoskeleton effectively. Manufacturer-generated contraindications and precautions for use of the Ekso (Ekso Bionics; **Figure 2**), ReWalk (ReWalk Robotics; **Figure 3**), and Indego (Parker Hannifin **Figure 4**) are shown in **Table 2**. An additional contraindication described by researchers and clinicians who investigate the devices, but not specifically described by manufacturers, is poor bone health.^{5,7,13-15,18,20-25} Inclusion and exclusion criteria based on bone health are not consistently defined and vary between studies. Some studies based criteria on bone density scores of the hip or lumbar spine,^{21,22} others performed x-rays to rule out recent lower extremity fractures,^{7,18,20} while other studies offered vague operational definitions of poor bone health.^{5,13} These varied, study-based, inclusion criteria depict multiple ways of assessing "bone health." Manufacturers have not come to an agreement on a gold standard approach or even

Table 1. Bionic devices and general device information as of January 2017

Device name	Company name	Height inclusion, cm	Weight inclusion, kg	ROM inclusion	Injury level	Additional
Ekso ²⁷	Ekso Bionics	152-193	≤100	Bilateral hip flexion 110° ≤12° knee contracture Neutral dorsiflexion	T4-L5 ^{31*} C7-T3 AIS D ^{31*} Triceps function	LLD (thigh <1.27 cm or lower leg <1.9 cm) Hip width <46 cm Stroke rehabilitation ^{31*}
Rewalk ⁵¹	ReWalk Robotics	160-190	≤100	Bilateral hip extension to 0° ≤10° knee contracture Neutral dorsiflexion	Rehabilitation: T4-T6 ^{52*} Personal use: T7-L5 ^{52*}	Personal use with supervision by trained companion ^{52*}
Indego ⁵³	Parker Hannifin	150-190	≤113	≤10° contracture at hips, knees ≤5° contracture at ankles	Personal use: T7-L5 ^{54*} Rehabilitation: T4-T6 ^{54*}	Hip width <42.2 cm Femur length from 35.3 to 47 cm Personal use with supervision by trained companion ^{54*} FES integration for research ⁵⁵
HAL ⁵⁶	Cyberdine	na	≤100	Non-severe limitation of ROM at hip, knee	Conus medullaris or cauda equina	Must present motor functions of hip and knee extensor Flexor muscle groups to be able to trigger HAL
WPAL ¹⁸	na	145-180	≤80	Non-severe contracture of limbs or spine	T4-L1 A or B C6-T3 considered on case-by-case basis	na
Phoenix ¹⁷	SuitX	160-187	≤91	≤35° hip flexion ≤20° knee flexion contracture	T4-L5	na
Axosuit ¹⁹	Axosuits	150-210	≤125	na	na	na
REX ⁴²	REX Bionics	na	≤100	na	na	na
MIND-WALKER ⁵⁷	na	na	na	na	na	Accommodate 90% of European population based on DINED database
Kinesis ³⁰	na	na	na	na	iSCI	FES integration Preserved hip flexion ability Partial ability to generate voluntary knee extension Paralysis of ankle joint Mild to severe spasticity

Note: Asterisk denotes FDA approval. DINED = Dutch anthropometry database; FES = functional electrical stimulation; HAL = Hybrid Assist Limb; iSCI = incomplete spinal cord injury; LLD = leg length discrepancy; na = not available, not published; ROM = range of motion; WPAL = Wearable Power Assist Locomotor.

Table 2. Manufacturer contraindications and precautions

	Ekso ²⁷	ReWalk ⁵¹	Indego ⁵³
Spasticity	C	C	C
Pressure sores	C	C	C
Heterotropic ossificans	P	C	C
Colostomy bag	P	-	C
Pregnancy	C	C	C
Cognitive/psychiatric condition	P	C	C
Uncontrolled autonomic dysreflexia	C	-	C
Spinal instability	C	-	C
Unresolved DVT	C	C	C
Orthostatic hypotension	P	-	C
Concurrent medical diagnosis	-	C	C
Lower limb prosthesis	-	-	C
Uncontrolled hypertension	-	-	C
Neurological injury other than SCI	-	-	C
Unhealed pelvic or limb fractures	-	-	C

Note: C = contraindication; DVT = deep vein thrombosis; P = precaution; SCI = spinal cord injury; - = not mentioned by manufacturer.

Figure 1. Phoenix (SuitX). Courtesy of SuitX and University of California at Berkeley.

the necessity of this measurement as few, if any, fracture-related adverse events have been published in current literature. A 2016 review found that out of 111 participants from 14 different studies who participated in bionic ambulation programs, only one fracture-related adverse event, a hairline talus fracture, was reported.²⁶

Figure 2. Ekso (Ekso Bionics).

The requirement for physician approval varies by device, although studies in which the devices are tested are typically conducted following physician clearance to screen for users with higher risk for injury or mortality associated with using the device.^{5,13,19,21-23,25,27,28} Some devices have more specific inclusion and exclusion criteria for use. For example, thigh and leg length discrepancies greater than 1.27 and 1.9 cm, respectively, or hip width greater than 18 in. (46 cm) exclude the use of the Ekso.^{5,7,27} Two studies by del-Ama and colleagues^{29,30} required participants using the Kinesis to have an incomplete conus medullaris injury, volitional hip flexion, partial voluntary knee extension, ankle joint paralysis, and mild to severe spasticity. The Kinesis bionic design differs the most from the other devices reported in the literature, as it is described as a hybrid knee-ankle-foot orthosis (KAFO).^{29,30} Studies in which the ReWalk, Ekso, and Indego are tested suggest differences between manufacturer height requirements and inclusion and exclusion criteria.^{5-7,13,21,22,27,28,31-34} In many cases, study criteria for

Figure 3. ReWalk (ReWalk Robotics). Courtesy of ReWalk Robotics.

body size are less inclusive than those of the device manufacturer, but criteria for injury level are more liberal (Table 1).

Assistive devices used with bionic exoskeletons for stability and balance

Most bionic exoskeletons require the use of assistive devices for all movement activities. The REX uses linear actuators³⁵ to provide user stability

Figure 4. Indego (Parker Hannifin). Courtesy of Parker Hannifin Corporation.

and balance and is thus the only exoskeleton that does not require the use of an assistive device. The MINDWALKER has been tested in non-injured individuals without assistive devices. However, when used by individuals with SCI, Gancet and colleagues³⁶ employed parallel bars and a tethered body harness for safety. In a systematic review,

Table 3. Bionic exoskeleton assistance levels

Assistance level	Spungen description ²⁵	Proposed description
Maximal	“The trainer had both hands on the pelvic band of the device and provided significant and frequent weight shift and balance support to the participant during the majority of the mobility activity.”	-Two hands on device/person and verbal cues -Support and assistance required at least 66% of the time
Moderate	“The trainer had both hands on the pelvic band or other part of the device and provided occasional weight shift and/or balance support to the participant during the mobility activity.”	-One or two hands on device/person and verbal cues -Support and assistance required from 33%-65% of the time
Minimal	“The trainer had one hand on the device and provided infrequent balance support.”	-One hand on device/person and verbal cues -Support and assistance required 5%-32% of the time
Close contact guard/no assist	“The trainer did not have either hand on the device, but was near enough to step in with assistance, if necessary.”	-Contact/verbal cues only as needed -Support and assistance required less than 5% of the time

Lajeunesse et al³⁵ claimed that an Ekso user could ambulate with the device when unassisted after first requiring crutches or a walker during bionic ambulation. This claim was neither referenced nor supported by the Ekso Bionics Clinical Training Guide,²⁷ which states that (a) “the Ekso device enables the patient to stand and walk with the assistance of a front rolling walker, crutches, or cane” and (b) “patients must use the Ekso under the direction of a physical therapist who has been trained in proper Ekso operation.” Another review states that exoskeleton users tend to start using a walker as an assistive device and progress to forearm crutches.³⁷ This review also reports that persons with a cervical level injury have been allowed to use a platform walker during training, possibly decreasing the need for hand-hold on a rolling walker or unimpaired grip strength.³⁷ We have experience with a single subject having limited grip strength due to incomplete cervical SCI who, when using a rolling walker for assistance, experienced pain, mild inflammation, and weakness at the common extensor tendon, bilaterally. This subject used a tenodesis assist to maintain his grip on the walker during training and in doing so induced an overuse type of injury (unpublished data). This issue may be avoided if patients use grip-assist gloves when permitted and deemed safe.

Assistance

Need for assistance by users is not always described in product literature for exoskeleton use, or it is sometimes poorly defined. In a pilot study

using the ReWalk, Spungen et al²⁵ established a scale for estimating assistance required during a practiced skill. These levels of assistance and proposed definitions are shown in **Table 3**.²⁵ Although this measure may not be applicable for every exoskeleton, a version could be adapted to create a standard assistance scale to reference while using exoskeletons. In addition to hands-on assistance, verbal cueing and external step initiation should be considered when demarcating assistance levels.

Proficiency when using bionic devices

The point at which users develop walking proficiency with exoskeletons remains undefined, although higher gait velocities and increased independence seem to represent proxy indicators. That stated, differences in users and bionic characteristics make an assessment of walking proficiency challenging. Factors to consider include user confidence, ratings of perceived exertion, assistance required, and ability to reach a specific speed or distance during a 6-minute walk test (6MWT). A proposed definition of proficiency may be the ability to use an exoskeleton device in an ambulatory mode requiring close guard or supervision assistance only. Louie et al³⁷ found that 84 exoskeleton users ambulated at an average of 0.26 m/s. This speed is not considered adequate for community ambulation. However, it is within a range found sufficient for household ambulation in iSCI.^{37,38} Louie et al³⁷ and others¹⁴ report that exoskeleton ambulators who required continuous

contact assistance walked slower than independent ambulators (walking velocities of 0.21 m/s and 0.26 m/s, respectively). Those who used the ReWalk and Indego (ambulation velocities of 0.26 m/s and 0.31 m/s, respectively) ambulated faster than those who used the Ekso and WPAL (0.14 m/s and 0.16 m/s, respectively).³⁷ When the 84 participants in this review were stratified based on injury completeness, those with an incomplete injury ambulated faster than those with a complete injury (0.32 m/s and 0.25 m/s, respectively).³⁷ Additionally, Louie et al³⁷ found a significant relationship between gait speeds and both lower injury level and training time in the device. One explanation for these observations is the more substantial core recruitment due to a lower injury level, which may permit less reliance on upper extremity support.³⁷ Notwithstanding, practice is reported to improve speed and accuracy of walking in every device.^{37,39}

It is important to note that not all of the studies included in this review measured gait velocity or did so using the same methods.³⁷ In some cases, ambulation velocity cited by Louie and colleagues was extrapolated using ambulation distance and time. However, not all studies have tested individuals with a goal of achieving maximum ambulation velocity.

Utility of Robotic Exoskeletons for SCI: Exercise or Community Ambulation?

Functional performance when using non-bionic orthoses is hindered by high energy demand during ambulation. This elevated energy cost is cited as the main limitation in the use of these devices for community ambulation, as such, many individuals prefer wheelchairs for locomotion.⁴⁰ Bionic exoskeletons afford individuals with SCI the opportunity to stand and walk overground; however, if the energy cost of bionic ambulation is high enough to elicit an exercise response, there may be a narrow utility for the use of these devices in community ambulation. Limited data address the metabolic demand of bionic ambulation in individuals with SCI; existing data evidence a wide range of responses.

A 2014 case series ($N = 3$) exploring cardio-metabolic responses to a 6-week bionic ambulation

training program in individuals with complete SCI found that bionic ambulation elicited energy expenditures and intensities similar to those observed in walking performed by non-injured individuals (1.4-2.6 kcal/min and 25%-41% of peak oxygen consumption [VO_{2peak}], respectively).⁷ Guidelines of the American College of Sports Medicine (ACSM) classify these intensities as “light to very light” and not likely to stimulate improvements in cardiorespiratory fitness.⁴¹ In a more recent study ($N = 4$),¹³ intensities during bionic ambulation were nearly 1.5 to 2.5 times greater, falling within the “moderate intensity” exercise category as defined by the ACSM. It should be noted that different exoskeletons and unique study methodologies place distinctive demands on the study subjects and may account for these apparently divergent findings. For example, in the latter study, data were collected during performance of a 6MWT, which would maximize ambulation velocity and energy cost, whereas the former study examined 60-minute bouts of walking without encouraging maximum ambulation velocity or effort. Care must, therefore, be taken when comparing data from studies that adopt different testing strategies or provide dissimilar user instructions.

Manufacturer Claims

Manufacturer websites geared toward potential users and rehabilitation specialists universally outline product claims for their device. Some statements targeted toward rehabilitation professionals discuss the ease of use, practicality, and benefits of adding exoskeleton training to standing and gait training protocols.^{32,33,42,43} The ReWalk website claims that it is the “most customizable exoskeleton” due to the adaptable fit that “optimizes safety, function, and joint alignment.”³⁴ SuitX claims to have created the “benchmark for exoskeletons” with the Phoenix.¹⁷ The website for the HAL even suggests that it is the first robotic device that can “lead to the possibility to walk” by teaching the brain to move the legs.⁴³ Claims made by other manufacturers include pain reduction and improved bowel and bladder function,⁴⁴ regaining personal freedom, and enhanced social reintegration.¹⁹ The Indego and

Phoenix websites state that the devices can be worn while seated in a wheelchair and can be donned or doffed independently, the Indego claims, with only one hand.^{17,33} These claims should be cautiously vetted so that consumers with SCI and their health care professionals can be as informed as possible.

Limitations of Bionic Exoskeletons

All bionic devices are delimited in community and rehabilitation use when compared to unimpaired walking. The cost for purchase and maintenance, limited battery life, community barriers and obstacle negotiation, need for upper extremity support, and caregiver assistance are among the barriers that constrain the routine use of the devices.

Battery life

Currently, the ReWalk reports the longest battery life at 8 hours.³⁵ The Indego and Ekso report a 4-hour battery life. The REX batteries can support 2 hours of continuous walking and no battery power is used in quiet standing, but the manufacturer claims that the device is designed for all-day use.^{35,42} The SuitX website states that the Phoenix can walk continuously for 4 hours or intermittently for 8 hours.¹⁷ Even with 8 hours of battery, these exoskeletons would not be able to provide assistance for the user throughout an entire day. Batteries add substantial weight to the devices, and prudent use would require an additionally charged set be maintained and available at all times.

Barriers to community ambulation

Obstacles readily found in the community, including stairs and ramps, are negotiable by only a select few of these devices. The International Residential Code (2006) has a minimum stair depth of 10 in. (25.4 cm) and a maximum step height of 7.75 in. (19.7 cm).⁴⁵ Under the Americans with Disabilities Act, the standard stair height can range from 4 to 7 in. (10.2-17.8 cm) and the stair depth can be greater than 11 in. (27.9 cm).⁴⁶ The REX can negotiate stairs, but the depth must be at least 12.1 in. (30.7 cm) and the maximum height 6

in. (15.2 cm). A user in the ReWalk can negotiate stairs but requires moderate assistance to do so.²⁵ The Indego exoskeleton was tested on 2 types of stair geometries in a single subject case study by an individual with a T10 American Spinal Injury Association Impairment Scale (AIS) A SCI. The height x depth dimensions of the 2 stairs were as follows: 7.25 x 11 in. (18.4 x 27.9 cm) and 7 x 11.75 in. (17.8 x 29.8 cm).⁴⁶ This case study found that the controller method that was implemented allowed the subject to ascend and descend these stairs in the Indego.⁴⁶ The Ekso manual²⁷ states that the intended use of the Ekso is in a dry, flat, rehabilitation setting with no ramps or slopes greater than 2% grade. The ability to make adjustments, such as increasing step height or relative walking angle, is helpful if a slightly steeper grade or floorings such as carpet or outdoor brick pavers are encountered. The ability to navigate stairs and ramps in select devices offers the user more freedom. However, to safely and confidently negotiate these obstacles, users should be aware of impending landscape.

User engagement with the environment and during daily activities is delimited by their need to use their hands during ambulation. The REX claims to be a hands-free device, but it requires joystick controller management by the user.³⁵ In quiet standing, a REX user is free to utilize both upper extremities. All other devices found in the literature require the use of upper extremities for support with a walker or crutches. In our work with the Ekso, users practice these tasks with both walkers and forearm crutches. This practice permits the users to better understand their limits of stability in the device and to begin trusting their ability to maintain a stable balance. Two studies involving the ReWalk have commented on the practice of double and single arm standing balance tasks using crutches during training.^{14,25} One of these studies includes pictures of a subject standing at a counter and performing overhead reaching into a cabinet while in the ReWalk.¹⁴ While this task and other community-related tasks are described in the “Progressive Goals of Mobility Training” section of the Asselin et al¹⁴ paper, translational outcomes of the single arm balance and other walking tasks to the community setting beyond training were not detailed.

Future Research

Next generations of exoskeletons may face some of the same issues that limited the use of the mechanical braces, such as excessive time consumption to don and doff, fear of falling, and the required use of an assistive device preoccupying the hands of the user. A randomized controlled trial by Arazpour et al⁴⁷ showed that people with an SCI could walk faster and longer with a powered exoskeleton than with a hip-knee-ankle-foot orthosis (HKAFO) and RGO, although the ambulation times of the latter were so slow as to raise the question of whether this is a reasonable comparison. Technological advances could potentially overcome the inadequacies of mechanical braces, although componentry and the technological level needed for a broader breakthrough in the rehab setting as well as community ambulation devices remain uncertain. Improving system components often adds cost and weight, which are 2 obstacles to more expanded use of the device. Enhancements in software can sometimes be provided for earlier generation braces, but the risk of owning an earlier bionic that cannot be retrofitted with existing hardware and software remains an unfavorable reality.

There is a general belief that rehabilitation programs initiated early after the SCI may improve locomotor function and should include repetitive and intensive gait training.⁴⁸ However, this is a very demanding and time-consuming process and requires high motivation and commitment toward this goal. This may not be a possibility or a priority for all patients. Based on 5 randomized controlled trials, Mehrholz et al⁴⁸ concluded in a systematic Cochrane review that there is insignificant evidence to suggest that one locomotor training strategy is superior for improving walking ability. Future studies should employ randomized, controlled crossover study designs, apply narrower inclusion and exclusion criteria, and increase study sample sizes to discriminate this potential use better.

Additional Applications for Bionic Exoskeletons

Clinics are using bionic exoskeletons therapeutically for a wide patient population, not

only SCI. The powered exoskeleton from Ekso Bionics is the only overground-walking exoskeleton with FDA approval for stroke rehabilitation, although studies examining this patient group have yet to be published. A systematic review of the HAL found beneficial effects on gait function and walking independence in a mixed population of neurological disorders, including stroke.⁴⁹ Other patient populations that may benefit from robotic gait training include multiple sclerosis, traumatic brain injury, cerebral palsy, and other neurological disorders that lead to lower extremity paresis.⁵⁰

Conclusion

Reciprocal stepping has been achieved for persons with SCI using bionic exoskeletons and upper body support. A wide array of devices with different functional and ambulatory characteristics have been brought to market for use in the rehabilitation and community settings. The ability of these devices to improve fitness and address secondary medical complications following SCI remains to be determined, although evidence suggests that the devices, qualifications for use, and benefits significantly differ from bionic to bionic. Early evidence points to improvements over earlier braces and walking systems when testing the energy needed to ambulate. Bionic devices that perform overground can be explored as aids to improve the ambulation kinetics for persons with spared motor function or impairment from SCI and other neurological diseases and disorders. Current use occurs primarily within rehabilitation facilities because of limited accessibility, cost of the devices, and the need for personnel to assist ambulation. Exoskeletons as primary community ambulation devices will only be practical when technological improvements provide safety and independence in walking at velocities approaching those of persons without disabilities and when community and environmental barriers to safe walking can be surmounted.

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