

Clinical Research Summary



Indego® has been developed in close coordination with clinicians and patients. Parker is committed to providing the most usable, effective and cost saving exoskeleton technology, backed by substantial clinical research. To that end, Parker has partnered with some of the world's leading rehabilitation centers to establish an ever-growing body of peer reviewed literature.

Topics in Spinal Cord Injury Rehabilitation

Vol: 24, Issue 1, Published: January 2018

Initial Outcomes from a Multicenter Study Utilizing the Indego Powered Exoskeleton in Spinal Cord Injury

C. Tefertiller, K. Hays, J. Jones, A. Jayaraman, C. Hartigan, T. Bushnik, and G. Forrest

Objective: To assess safety and mobility outcomes utilizing the Indego powered exoskeleton in indoor and outdoor walking conditions with individuals previously diagnosed with a spinal cord injury (SCI). **Methods:** We conducted a multicenter prospective observational cohort study in outpatient clinics associated with 5 rehabilitation hospitals. A convenience sample of nonambulatory individuals with SCI (N = 32) completed an 8-week training protocol consisting of walking training 3 times per week utilizing the Indego powered exoskeleton in indoor and outdoor conditions. Participants were also trained in donning/doffing the exoskeleton during each session. Safety measures such as adverse events (AEs) were monitored and reported. Time and independence with donning/doffing the exoskeleton as well as walking outcomes to include the 10-meter walk test (10MWT), 6-minute walk test (6MWT), Timed Up & Go test (TUG), and 600-meter walk test were evaluated from midpoint to final evaluations. *See the [publication](#)*

IEEE International Conference of Engineering in Medicine and Biology Science

Conference Proceedings 2015: 4671-4

Preliminary assessment of variable geometry stair ascent and descent with a powered lower limb orthosis for individuals with paraplegia

A. Ekelem, S. Murray, and M. Goldfarb

This paper describes a controller for a lower-limb exoskeleton that enables variable-geometry stair ascent and descent for persons with lower limb paralysis. The controller was evaluated on a subject with T10 complete spinal cord injury (SCI) on two staircases, one with a riser height and tread depth of 18.4 × 27.9 cm (7.25 × 11 in) and the other 17.8 × 29.8 cm (7 × 11.75 in). The controller enabled ascent and descent of both staircases without explicit tuning for each, and with an average step rate of 12.9 step/min during ascent and 14.6 step/min during descent. *See the [publication](#)*

IEEE International Conference of Engineering in Medicine and Biology Science

Conference Proceedings 2014: 4083 - 4086

An Assistive Controller for a Lower-Limb Exoskeleton for Rehabilitation after Stroke, and Preliminary Assessment Thereof

K.H. Ha, S.A. Murray, and M. Goldfarb

This paper describes a novel controller, intended for use in a lower-limb exoskeleton, to aid gait rehabilitation in patients with hemiparesis after stroke. The controller makes use of gravity compensation, feedforward movement assistance, and reinforcement of isometric joint torques to achieve assistance without dictating the spatiotemporal nature of joint movement. The patient is allowed to self-select walking speed and is able to make trajectory adaptations to maintain balance without interference from the controller. The governing equations and the finite state machine which comprise the system are described herein. The control architecture was implemented in a lower-limb exoskeleton and a preliminary experimental assessment was conducted in which a patient with hemiparesis resulting from stroke walked with assistance from the exoskeleton. The patient exhibited improvements in fast gait speed, step length asymmetry, and stride length in each session, as measured before and after exoskeleton training, presumably as a result of using the exoskeleton.

See the [publication](#).

IEEE Transactions on Neural Systems and Rehabilitation Engineering

Issue: 99, Published: April 23rd, 2015

An Approach for the Cooperative Control of FES With a Powered Exoskeleton During Level Walking for Persons With Paraplegia

K.H. Ha, S.A. Murray, and M. Goldfarb

This paper describes a hybrid system that combines a powered lower limb exoskeleton with functional electrical stimulation (FES) for gait restoration in persons with paraplegia. The general control structure consists of two control loops: a motor control loop, which utilizes joint angle feedback control to control the output of the joint motor to track the desired joint trajectories, and a muscle control loop, which utilizes joint torque profiles from previous steps to shape the muscle stimulation profile for the subsequent step in order to minimize the motor torque contribution required for joint angle trajectory tracking. The implementation described here incorporates stimulation of the hamstrings and quadriceps muscles, such that the hip joints are actuated by the combination of hip motors and the hamstrings, and the knee joints are actuated by the combination of knee motors and the quadriceps. In order to demonstrate efficacy, the control approach was implemented on three paraplegic subjects with motor complete spinal cord injuries ranging from levels T6 to T10. Experimental data indicates that the cooperative control system provided consistent and repeatable gait motions and reduced the torque and power output required from the hip and knee motors of the exoskeleton compared to walking without FES.

See the [publication](#).

Topics in Spinal Cord Injury Rehabilitation, American Spinal Injury Association

Vol: 21 No. 2, Published: April 12th, 2015

Mobility Outcomes Following Five Training Sessions with a Powered Exoskeleton

C. Hartigan, C. Kandilakis, S. Dalley, M. Clausen, E. Wilson, S. Morrison, S. Etheridge, and R. Farris

Objective: This study was conducted to evaluate mobility outcomes for individuals with SCI after 5 gait-training sessions with a powered exoskeleton, with a primary goal of characterizing the ease of learning and usability of the system.

Methods: Sixteen subjects with SCI were enrolled in a pilot clinical trial at Shepherd Center, Atlanta, Georgia, with injury levels ranging from C5 complete to L1 incomplete. An investigational Indego exoskeleton research kit was evaluated for ease of use and efficacy in providing legged mobility. Outcome measures of the study included the 10-meter walk test (10MWT) and the 6-minute walk test (6MWT) as well as measures of independence including donning and doffing times and the ability to walk on various surfaces. **Results:** At the end of 5 sessions (1.5 hours per session), average walking speed was 0.22 m/s for persons with C5-6 motor complete tetraplegia, 0.26 m/s for T1-8 motor complete paraplegia, and 0.45 m/s for T9-L1 paraplegia. Distances covered in 6 minutes averaged 64 meters for those with C5-6, 74 meters for T1-8, and 121 meters for T9-L1. Additionally, all participants were able to walk on both indoor and outdoor surfaces. **Conclusions:** Results after only 5 sessions suggest that persons with tetraplegia and paraplegia learn to use the Indego exoskeleton quickly and can manage a variety of surfaces. Walking speeds and distances achieved also indicate that some individuals with paraplegia can quickly become limited community ambulators using this system.

See the [publication](#).

Topics in Spinal Cord Injury Rehabilitation, American Spinal Injury Association

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Acute Cardiorespiratory and Metabolic Responses During Exoskeleton-Assisted Walking Overground Among Persons with Chronic Spinal Cord Injury

N. Evans, C. Hartigan, C. Kandilakis, E. Pharo, and I. Clesson

Objective: The purpose of this pilot study was to evaluate the acute cardiorespiratory and metabolic responses associated with exoskeleton-assisted walking overground and to determine the degree to which these responses change at differing walking speeds. **Methods:** Five subjects (4 male, 1 female) with chronic SCI (AIS A) volunteered for the study. Expired gases were collected during maximal graded exercise testing and two, 6-minute bouts of exoskeleton-assisted walking overground. Outcome measures included peak oxygen consumption ($\dot{V}O_{2peak}$), average oxygen consumption ($\dot{V}O_{2avg}$), peak heart rate (HR_{peak}), walking economy, metabolic equivalent of tasks for SCI (MET_{SCI}), walk speed, and walk distance. **Results:** Significant differences were observed between walk-1 and walk-2 for walk speed, total walk distance, $\dot{V}O_{2avg}$, and MET_{SCI}. Exoskeleton-assisted walking resulted in % $\dot{V}O_{2peak}$ range of 51.5% to 63.2%. The metabolic cost of exoskeleton-assisted walking ranged from 3.5 to 4.3 MET_{SCI}. **Conclusion:** Persons with motor-complete SCI may be limited in their capacity to perform physical exercise to the extent needed to improve health and fitness. Based on preliminary data, cardiorespiratory and metabolic demands of exoskeleton-assisted walking are consistent with activities performed at a moderate intensity.

See the [publication](#).

IEEE Transactions on Neural Systems and Rehabilitation Engineering

Vol:22 Issue:3, Published: May 2014

A Preliminary Assessment of Legged Mobility Provided by a Lower Limb Exoskeleton for Persons With Paraplegia

R. Farris, H.A. Quintero, S.A. Murray, K.H. Ha, C. Hartigan, and M. Goldfarb

This paper presents an assessment of a lower limb exoskeleton for providing legged mobility to people with paraplegia. In particular, the paper presents a single-subject case study comparing legged locomotion using the exoskeleton to locomotion using knee-ankle-foot orthoses (KAFOs) on a subject with a T10 motor and sensory complete injury. The assessment utilizes three assessment instruments to characterize legged mobility, which are the timed up-and-go test, the Ten-Meter Walk Test (10 MWT), and the Six-Minute Walk Test (6 MWT), which collectively assess the subject's ability to stand, walk, turn, and sit. The exertion associated with each assessment instrument was assessed using the Physiological Cost Index. Results indicate that the subject was able to perform the respective assessment instruments 25%, 70%, and 80% faster with the exoskeleton relative to the KAFOs for the timed up-and-go test, the 10 MWT, and the 6 MWT, respectively. Measurements of exertion indicate that the exoskeleton requires 1.6, 5.2, and 3.2 times less exertion than the KAFOs for each respective assessment instrument. The results indicate that the enhancement in speed and reduction in exertion are more significant during walking than during gait transitions.

See the [publication](#)

IEEE International Conference of Engineering in Medicine and Biology Society

Conference Proceedings 2012:1908-1911

Performance evaluation of a lower limb exoskeleton for stair ascent and descent with paraplegia

R. Farris, H. Quintero and M. Goldfarb

This paper describes the application of a powered lower limb exoskeleton to aid paraplegic individuals in stair ascent and descent. A brief description of the exoskeleton hardware is provided along with an explanation of the control methodology implemented to allow stair ascent and descent. Tests were performed with a paraplegic individual (T10 complete injury level) and data is presented from multiple trials, including the hip and knee joint torque and power required to perform this functionality. Joint torque and power requirements are summarized, including peak hip and knee joint torque requirements of 0.75 Nm/kg and 0.87 Nm/kg, respectively, and peak hip and knee joint power requirements of approximately 0.65 W/kg and 0.85 W/kg, respectively.

See the [publication](#)

IEEE International Conference of Engineering in Medicine and Biology Society
Conference Proceedings 2012:344-347

Enhancing Stance Phase Propulsion during Level Walking by Combining FES with a Powered Exoskeleton for Persons with Paraplegia

K. Ha, H. Quintero, R. Farris, M. Goldfarb

This paper describes the design and implementation of a cooperative controller that combines functional electrical stimulation (FES) with a powered lower limb exoskeleton to provide enhanced hip extension during the stance phase of walking in persons with paraplegia. The controller utilizes two sources of actuation: the electric motors of the powered exoskeleton and the user's hamstrings activated by FES. It consists of a finite-state machine (FSM), a set of proportional-derivative (PD) controllers for the exoskeleton and a cycle-to-cycle adaptive controller for muscle stimulation. Level ground walking is conducted on a single subject with complete T10 paraplegia. Results show a 34% reduction in electrical power requirements at *the hip joints during the stance phase of the gait cycle with the cooperative controller compared to using electric motors alone.* See the [publication](#)

ASME Journal of Medical Devices

Vol:6 No.4, Published: December, 2012

A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons With Paraplegia

H. Quintero, R. Farris, and M. Goldfarb

This paper describes a control method for a lower limb powered exoskeleton that enables a paraplegic user to perform sitting, standing, and walking movements. The different maneuvers are commanded by the user based on postural information measured by the device. The proposed user interface and control structure was implemented on a powered lower limb orthosis, and the system was tested on a paraplegic subject with a T10 complete injury. Experimental data is presented that indicates the ability of the proposed control architecture to provide appropriate user-initiated control of sitting, standing, and walking. The authors also provide a link to a video that qualitatively demonstrates the user's ability to independently control basic movements via the proposed control method. See the [publication](#)

IEEE International Conference of Engineering in Medicine and Biology Society

Conference Proceedings 2012:3360-3363

Preliminary Assessment of the Efficacy of Supplementing Knee Extension Capability in a Lower Limb Exoskeleton with FES

H. Quintero, R. Farris, K. Ha, and M. Goldfarb

The authors describe a cooperative controller that combines the knee joint actuation of an externally powered lower limb exoskeleton with the torque and power contribution from the electrically stimulated quadriceps muscle group. The efficacy of combining these efforts is experimentally validated with a series of weighted leg lift maneuvers. Measurements from these experiments indicate that the control approach effectively combines the respective efforts of the motor and muscle, such that good control performance is achieved, with substantial torque and energy contributions from both the biological and non-biological actuators. See the [publication](#)

2011 IEEE International Conference on Rehabilitation Robotics

Conference Proceedings 2011:5975481

Control and Implementation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals

H. Quintero, R. Farris, and M. Goldfarb

This paper describes a powered lower-limb orthosis that is intended to provide gait assistance to spinal cord injured (SCI) individuals by providing assistive torques at both hip and knee joints, along with a user interface and control structure that enables control of the powered orthosis via upper-body influence. The orthosis and control structure was experimentally implemented on a paraplegic subject (T10 complete) in order to provide a preliminary characterization of its capability to provide basic walking. Data and video is presented from these initial trials, which indicates that the orthosis and controller are able to effectively provide walking within parallel bars at an average speed of 0.8 km/hr. *See the [publication](#)*

Topics in Spinal Cord Injury Rehabilitation, American Spinal Injury Association

Vol:17 No.1, Published: July 11th, 2011

A Powered Lower Limb Orthosis for Providing Legged Mobility in Paraplegic Individuals

H. Quintero, R. Farris, C. Hartigan, I. Clesson, and M. Goldfarb

This paper presents preliminary results on the development of a powered lower limb orthosis intended to provide legged mobility (with the use of a stability aid, such as forearm crutches) to paraplegic individuals. The orthosis contains electric motors at both hip and both knee joints, which in conjunction with ankle-foot orthoses, provides appropriate joint kinematics for legged locomotion. The paper describes the orthosis and the nature of the controller that enables the SCI patient to command the device, and presents data from preliminary trials that indicate the efficacy of the orthosis and controller in providing legged mobility. *See the [publication](#)*

Preliminary Evaluation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals

R. Farris, H. Quintero and M. Goldfarb

This paper describes a powered lower-limb orthosis that is intended to provide gait assistance to spinal cord injured (SCI) individuals by providing assistive torques at both hip and knee joints. The orthosis has a mass of 12 kg and is capable of providing maximum joint torques of 40 Nm with hip and knee joint ranges of motion from 105° flexion to 30° extension and 105° flexion to 10° hyperextension, respectively. A custom distributed embedded system controls the orthosis with power being provided by a lithium polymer battery which provides power for one hour of continuous walking. In order to demonstrate the ability of the orthosis to assist walking, the orthosis was experimentally implemented on a paraplegic subject with a T10 complete injury. Data collected during walking indicates a high degree of step-to-step repeatability of hip and knee trajectories (as enforced by the orthosis) and an average walking speed of 0.8 km/hr. The electrical power required at each hip and knee joint during gait was approximately 25 and 27 W, respectively, contributing to the 117 W overall electrical power required by the device during walking. A video of walking corresponding to the aforementioned data is included in the supplemental material.

See the [publication](#)



Parker Hannifin Corporation
Human Motion & Control
1390 Highland Rd.
Macedonia, Ohio 44056 U.S.A.
1.844.846.3346
support.indego@parker.com

Learn more at indego.com