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

Nicholas Evans, MHS,[1,2] Clare Hartigan, MPT,[3] Casey Kandilakis, DPT,[3] Elizabeth Pharo, MPT,[1] and Ismari Clesson, RN, MSCN[3]

[1]*Beyond Therapy, Shepherd Center, Atlanta, Georgia;* [2]*Hulse Spinal Cord Injury Laboratory, Shepherd Center, Atlanta, Georgia;* [3]*Virginia C. Crawford Research Institute, Shepherd Center, Atlanta, Georgia*

Background: Lower extremity robotic exoskeleton technology is being developed with the promise of affording people with spinal cord injury (SCI) the opportunity to stand and walk. The mobility benefits of exoskeleton-assisted walking can be realized immediately, however the cardiorespiratory and metabolic benefits of this technology have not been thoroughly investigated. **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 ($METs_{sci}$), 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 $METs_{sci}$. 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 $METs_{sci}$. **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. **Key words:** *cardiovascular physiology, energy metabolism, exercise therapy, oxygen consumption, physical fitness, spinal cord injuries, walking*

Walking is a fundamental component of human movement requiring lower limb activation to initiate steps and support the body's weight during load bearing.[1,2] The increased physical workload demanded by walking stimulates the cardiorespiratory system to increase the delivery of oxygen to working muscles.[3] In noninjured adults, the combination of increased lower limb activation and cardiorespiratory stimulation can elicit a metabolic response 3 to 8 times higher than the resting metabolic rate depending on walking speed and loading conditions.[4,5] As a result, walking, when performed with sufficient intensity and duration, is often cited as an easy and effective means of improving cardiorespiratory fitness, increasing daily energy expenditure, and reducing the risk of chronic health conditions such as cardiovascular and metabolic disease.[6-8]

Spinal cord injury (SCI) often results in immediate and permanent paralysis of the lower limbs and trunk. Depending on the level and severity of injury, cardiorespiratory function may also be impaired due to disruption of the autonomic nervous system and weakness and stiffness of the muscles involved in ventilation.[9-12] For persons with lower limb paralysis, standing and walking capacity are also limited. As a result, a cascade of secondary health complications often accompanies SCI including decreased bone mineral density,[13] increased adiposity,[14,15] decreased cardiorespiratory fitness,[12] impaired

Corresponding author: Nicholas Evans, MHS, Beyond Therapy, Shepherd Center, 2020 Peachtree Road, NW, Atlanta, GA 30309; phone: 404-590-9565; e-mail: nicholas_evans@shepherd.org

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metabolic function,[16] and accelerated physical deconditioning.[17,18] Consequently, persons with chronic, motor-complete SCI often find themselves at the lowest end of the fitness spectrum.[19,20] Fortunately, a growing body of evidence suggests that increased participation in physical activity and exercise may mitigate the effects of SCI on long-term secondary health complications.[17,18,21-27] Thus, clinicians, researchers, and device manufacturers continue to investigate new and innovative strategies for improving mobility, physical conditioning, and health after SCI.

Body weight–supported treadmill training using lower extremity robotic exoskeleton technology was initially implemented in SCI rehabilitation with the aim of providing task-specific, motor-patterned activity to promote neuroplasticity and improve locomotor function.[28,29] Studies have begun to explore the cardiorespiratory and metabolic demands of exoskeleton-assisted treadmill walking and its effect on health outcomes following SCI.[30-33] Recent advances in robotic exoskeleton technology have produced a variety of devices that allow persons with SCI to walk overground. Our team was interested in exploring the potential for these devices to elicit the cardiorespiratory and metabolic responses needed to mitigate the long-term comorbidities often associated with persons with chronic motor-complete SCI.

Unlike robotic devices designed for treadmill training, emerging exoskeleton technologies designed for overground use offer persons with SCI the opportunity to stand and walk outside the constraints of a treadmill.[34-36] The mobility benefits of these new technologies can be realized immediately by assisting the user with overground walking in the home and community; however the therapeutic benefits of these devices are unknown. Consequently, it is not clear whether users can walk at speeds and intensities sufficient to positively affect health and fitness outcomes. Therefore, the purpose of this pilot study was to evaluate the acute cardiorespiratory and metabolic responses associated with exoskeleton-assisted walking overground among persons with SCI and to determine the degree to which the metabolic and cardiorespiratory responses change during different walking speeds.

Methods

Inclusion and exclusion criteria

To be enrolled in the study, participants were required to have motor-complete SCI (American Spinal Injury Association Impairment Scale [AIS] classification A or B[37]) at the level of C5 or lower, be at least 18 years of age, fall within a height range of 1.54 to 1.83 meters, have a body weight ≤ 113.4 kg, and be medically cleared for locomotor training. The exclusion criteria were as follows: (a) any skin comprise that interfaced with the device, (b) pregnancy, (c) poor bone health, (d) lower extremity spasticity score in any joint exceeding 3 out of 4 (Modified Ashworth Scale), (e) unresolved deep vein thrombosis, (f) uncontrolled autonomic dysreflexia (self-report), (g) lower extremity joint contractures exceeding 10° at hips, knees or ankles, or (h) any exercise contraindications as described by the American College of Sports Medicine (ACSM). Exclusion criteria were assessed through a combination of clinical evaluation, medical record examination, and self-report.

Participants

Participation of human subjects was approved by an institutional review board prior to initiation of the study. Written and verbal informed consent was obtained from all participants. Five participants (4 males, 1 female) aged 28 to 51 years with SCI (AIS classification A) between the levels of T6 and T12 and with a mean height of 1.80 meters and mean body weight of 70 kg were recruited from a convenience sample of patients at a nonprofit rehabilitation hospital and were enrolled in the study. Participant demographics and baseline characteristics are summarized in **Table 1**.

Device description

Detailed descriptions of the exoskeleton device used in this study (Indego, Parker Hannifin Corporation, Macedonia, OH) have been published elsewhere.[34,38] Participants completed all overground walking tests while in the "mobility mode" of the Indego. The mobility mode allows the user to actuate motion by postural changes that command the Indego to stand, walk, stop,

Table 1. Participant demographics and baseline characteristics

Subject no.	Age class, years	Height, m	Weight, kg	BMI	Gender	GXT $\dot{V}O_{2peak}$, mL/kg/min	TSI class, years	NLI	AIS class	Exoskeleton sessions	LOA
1	16-30	1.80	66	20.4	M	20.8	1-5	T7	A	10	S, RW
2	31-45	1.72	59	19.9	F	20.8	16-20	T8	A	6	S, RW
3	31-45	1.85	77	22.5	M	16.0	11-15	T10	A	6	S, FC
4	46-60	1.78	66	20.8	M	15.6	6-10	T12	A	5	S, FC
5	46-60	1.85	80	23.4	M	–	6-10	T6	A	5	S, RW
Mean ± *SD*	42 ± 9	1.80 ± 0.05	70 ± 9	21.4 ± 1.5	–	18.3 ± 2.9	11 ± 6	–	–	6 ± 2	–

Note: AIS = American Spinal Injury Association; BMI = body mass index; FC = forearm crutches; GXT = graded exercise test; LOA = level of assistance; NLI = neurological level of injury; RW = rolling walker; S = supervision; TSI = time since injury; $\dot{V}O_{2peak}$ = peak oxygen consumption.

or sit with 100% powered robotic assistance. Step trajectories are adjustable for posture, speed, height, and length.

Protocol

Participants completed 2 test sessions on nonconsecutive days. Each participant performed a maximal graded exercise test (GXT) using an arm cycle ergometer to determine peak cardiorespiratory capacity ($\dot{V}O_{2peak}$) followed by two 6-minute walk tests (6MWT) using the Indego. In both the GXT and the walking tests, expired gases were continuously analyzed by an open-circuit indirect calorimetry system (Oxycon Mobile; CareFusion Corporation, San Diego, CA) with integrated heart rate monitor. Breath-by-breath measurements were averaged over 30-second periods. Heart rate was assessed by placing an integrated recording band (Polar Heart Rate Monitor; Polar Electro Inc., Lake Success, NY) on the participant's chest, which then transmitted wireless signals to the Oxycon Mobile device for data collection.

GXT

Participants completed a maximal GXT using an arm cycle ergometer (Biodex Upper Body Cycle, 950-164; Biodex Medical Systems, Shirley, NY) on a non-exoskeleton walking day. After 10 minutes of seated rest, participants began cycling at 10 Watts and the workload was increased by 20 Watts every minute thereafter. Participants were instructed to maintain a cadence of 50 to 60 revolutions/minute as indicated on the arm cycle ergometer digital display. Participants were considered to have reached [$\dot{V}O_{2peak}$ based on attainment of 2 of the following 3 criteria: a plateau in oxygen consumption ($\dot{V}O_2$) despite an increase in workload, a respiratory exchange ratio (RER) value >1.10, and/or volitional exhaustion when a cadence of 50 revolutions/minute could not be maintained. Blood pressure was assessed by auscultation at rest and during recovery.

6MWT

Participants completed two 6MWTs, as previously described,[39] in a straight hallway measuring 30.5 meters in length. To ensure participants were accustomed to walking in the Indego, participants completed a minimum of 5 walking sessions in the device prior to testing. All participants walked with close supervision provided by a trained clinician. Participants ambulated using their preferred stability aid (either forearm crutches or front-wheeled rolling walker). During the first 6MWT (walk-1), participants were instructed to "walk at a self-selected, comfortable speed." During the second 6MWT (walk-2), participants were asked to "walk safely but as quickly as possible." Expired gases were collected continuously to determine cardiorespiratory and metabolic response during each walk test under the following conditions: 3 minutes of seated rest, 3 minutes of standing, 6 minutes of exoskeleton-assisted walking, 3 minutes of standing. Walk-1 and walk-2 were separated by 5 minutes of seated rest to allow for cardiorespiratory recovery between walking bouts. Rating of perceived exertion (RPE) using Borg's 6-20 scale[40] was assessed at the beginning and immediately following each 6MWT.

Outcome measures

Mobility outcomes

For each walk scenario, walking distance was measured as the total distance travelled in meters over 6 minutes. Walking speed was calculated by dividing the total distance covered during each walk test by the total walk time and was expressed in meters/second (m/s).

Cardiorespiratory and metabolic outcomes

Cardiorespiratory and metabolic outcome measures obtained during the GXT and the two 6MWTs included $\dot{V}O_{2peak}$ and average oxygen consumption ($\dot{V}O_{2avg}$) reported in milliliters of oxygen consumed per kilogram of body weight per minute (mL/kg/min) and peak heart rate (HR_{peak}) reported in heart beats per minute (beats/min). Relative cardiorespiratory demand of exoskeleton-assisted walking was calculated by dividing $\dot{V}O_{2avg}$ (obtained during walking) by $\dot{V}O_{2peak}$ (obtained from the GXT) and reported as a percentage of $\dot{V}O_{2peak}$ (%$\dot{V}O_{2peak}$). Walking economy was determined by calculating the rate of oxygen consumption per distance walked and was reported in liters of oxygen consumed per meter (L/m). Energy expenditure was expressed in terms of metabolic equivalent of tasks (METs) where 1 MET is equal to the energy expended during seated rest. For persons with SCI, 1 MET was set at 2.7 mL/kg/min and reported as $METs_{sci}$.[20]

Data analysis

Descriptive statistics were used to describe the sample and the primary outcome measures. Outcome variables obtained during walking were analyzed with matched pairs *t* tests to determine whether any statistically significant differences existed between the 2 walk scenarios. Statistical significance was set at $\alpha = 0.05$ for all analyses. Given the small sample size ($N = 5$), the data were examined for skew; finding little, we chose to report values as mean ± standard deviation (*SD*) rather than median and minimum/maximum range.

Results

Exoskeleton-assisted walking (mobility) outcomes

Differences were observed between walk-1 and walk-2 for both walking speed (0.19 ± 0.01 m/s and 0.27 ± 0.05 m/s, respectively) and total walk distance (67.40 ± 3.76 m and 95.93 ± 18.64 m, respectively). **Table 2** provides a summary of the mobility outcomes of exoskeleton-assisted walking for all participants.

Table 2. Total distance and walking speed following exoskeleton-assisted walking overground

Subject no.	Walk-1 distance, m	Walk-2 distance, m	Walk-1 speed, m/s	Walk-2 speed, m/s
1	62.83	90.14	0.17	0.25
2	68.88	92.06	0.19	0.26
3	68.93	128.46	0.19	0.36
4	72.05	87.68	0.20	0.24
5	64.30	81.30	0.18	0.23
Mean ± *SD*	67.40 ± 3.76	95.93 ± 18.64*	0.19 ± 0.01	0.27 ± 0.05**

*Significant difference in total distance walked between walk-1 and walk-2 ($P < .05$).

**Significant difference in walking speed between walk-1 and walk-2 ($P < .05$).

Cardiorespiratory and metabolic response

Four out of 5 participants completed the maximal GXT prior to exoskeleton-assisted walking. Participant 5 was unable to complete the GXT due to unavoidable scheduling conflicts. Therefore data from 4 participants were used to calculate mean $\dot{V}O_{2peak}$ for the sample population. Mean $\dot{V}O_{peak}$ was 18.3 ± 2.9 mL/kg/min (**Table 1**). A difference in $\dot{V}O_{2avg}$ was found between walk-1 and walk-2. Despite an increase in %$\dot{V}O_{2peak}$ of 11.7% and an increase in HR_{peak} of 21 beats/min, no differences were found for these outcomes between the 2 walk scenarios. Outcomes for $\dot{V}O_{2avg}$, HR_{peak}, and %$\dot{V}O_{2peak}$ are reported in **Table 3**.

The metabolic cost and efficiency of exoskeleton-assisted walking at 2 gait speeds was determined by calculating the mean $METs_{sci}$ value and walking economy for each walk scenario. Differences were observed between $METs_{sci}$ for walk-1 and walk-2. No significant differences were observed in walking economy between walk-1 and walk-2; however the faster walk scenario (walk-2) did result in a lower volume of oxygen consumed per meter walked. **Table 3** provides a summary of walking economy and $METs_{sci}$ for all participants.

Discussion

Limited data are available on the cardiorespiratory and metabolic responses to walking overground using a robotic exoskeleton device.[41] To our knowledge, this study is the first to demonstrate that exoskeleton-assisted walking overground can be performed at an intensity considered to be moderate according to the ACSM and that an increase in walking speed is associated with an increase in metabolic demand even among persons with motor-complete SCI.

Exoskeleton-assisted walking (mobility) outcomes

Despite the small sample size, differences between walk-1 and walk-2 were observed for both speed and distance. The total walk distance and average walk speed completed during the 2 walk scenarios were within ranges consistent with previous reports on speed and distance achieved during exoskeleton-assisted walking overground.[34,35,42] The mean change in 6MWT distance between walk-1 and walk-2 (Δ 28.53 m) exceeded the standard error of measurement as previously described for the 6MWT and SCI (Δ 16.5 m).[43] The increased distance covered during the second "faster" walk test, compared to the first, is likely due to the user's ability to volitionally control the exoskeleton and walking speed and not simply due to random measurement error inherent in the 6MWT itself. The ability to volitionally control the exoskeleton device in real time may allow the users to self-select walking speed based on the conditions in which they find themselves without having to stop and change settings and parameters within the device. Future investigations are needed in order to better understand to what extent increases in walking speed and distance are affected by changes in device settings or the user's ability to volitionally control the exoskeleton device.

Cardiorespiratory response during exoskeleton-assisted walking

Direct comparisons of our findings to previously published data on cardiorespiratory demands associated with exoskeleton-assisted walking overground are limited. One study[42] has reported cardiorespiratory data during overground walking using an exoskeleton device; contrary to our current findings, the investigators reported cardiorespiratory demands nearly 1.5 to 2.5 times lower than those observed in our study. Two distinctions between this study and the former study may account for these contrasting outcomes. First, different robotic exoskeletons were used in each study and each device may have placed unique physical demands on the user when attempting to actuate steps. Second, participants in our study were asked to walk at a self-selected pace but only for 6 minutes, whereas participants in the earlier study walked for 1 hour and were allowed to stop and rest as desired. It is likely that had we asked participants to walk for 1 hour, they may not have been able to sustain the same walk speed, would have likely needed rest breaks, and consequently would have experienced lower cardiorespiratory responses and relative

Table 3. Cardiorespiratory and metabolic response during exoskeleton-assisted walking overground

Variable	Subject no.	Walk-1	Walk-2
$\dot{V}O_{2avg}$, mL/kg/min	1	8.2	9.6
	2	9.9	11.1
	3	9.3	13.1
	4	9.5	11.1
	5	10.4	12.6
Mean ± *SD*		9.5 ± 0.8	11.5 ± 1.4*
HR_{peak}, beats/min	1	82	93
	2	105	122
	3	143	174
	4	118	147
	5	159	176
Mean ± *SD*		121 ± 30	142 ± 35
$\%\dot{V}O_{2peak}$	1	39.4	46.2
	2	47.6	53.4
	3	58.1	81.9
	4	60.9	71.2
	5	–	–
Mean ± *SD*		51.5 ± 9.9	63.2 ± 16.3
Walking economy, L/m	1	0.05	0.04
	2	0.05	0.04
	3	0.06	0.05
	4	0.05	0.05
	5	0.08	0.07
Mean ± *SD*		0.06 ± 0.01	0.05 ± 0.01
$METs_{sci}$	1	3.0	3.6
	2	3.7	4.1
	3	3.4	4.9
	4	3.5	4.1
	5	3.9	4.7
Mean ± *SD*		3.50 ± 0.30	4.26 ± 0.51**

Note: HR_{peak} = peak heart rate; $METs_{sci}$ = metabolic equivalent of tasks for persons with spinal cord injury; $\%\dot{V}O_{2peak}$ = percentage of peak oxygen consumption; $\dot{V}O_{2avg}$ = average oxygen consumption.
*Significant difference in $\dot{V}O_{2avg}$ between walk-1 and walk-2 ($P < .05$).
**Significant difference in $METs_{sci}$ between walk-1 and walk-2 ($P < .05$).

intensities. Additional research with a larger sample size and extended walking bouts of up to an hour in duration are required in order to make more direct comparisons.

Although limited research exists on exoskeleton-assisted walking overground, some relevant comparisons can be drawn from research investigating the cardiorespiratory demands associated with robotic exoskeleton-assisted treadmill walking. Jack et al[44] compared the cardiorespiratory response of active versus passive walking during exoskeleton-assisted treadmill training in motor-incomplete SCI. The investigators concluded that treadmill training using a robotic exoskeleton, when performed passively, was insufficient to increase cardiorespiratory fitness and that individuals must actively contribute to stepping in order to produce a cardiorespiratory response sufficient to induce a positive training effect. This evidence suggests that exoskeleton devices requiring more active involvement in body weight support, postural control, and step initiation may elicit a greater cardiorespiratory training effect than a more passive device. In fact, when comparing the cardiorespiratory demands of exoskeleton-assisted treadmill training[31] to exoskeleton-assisted walking overground, participants in the present study, when walking at faster speeds, demonstrated twice the cardiorespiratory response to that of treadmill walking (**Table 4**). This observation provides valuable insight as to the potential cardiorespiratory benefits associated with exoskeleton-assisted walking overground for persons with motor-complete SCI.

Metabolic response during exoskeleton-assisted walking

Understanding the metabolic response to exoskeleton-assisted walking overground is of value for both the clinician and consumer. The metabolic energy cost of activity can be used to calculate walking economy, to determine how walking efficiency can be improved, to provide a means of quantifying walking intensity so that appropriate recommendations for therapeutic use can be made, and to allow for direct comparison between the physiological demands related to various types of physical activity and exercise.

All participants in our study demonstrated a small but consistent improvement in walking economy at faster walking speeds. Kressler and colleagues[42] reported a similar finding among 3 participants who completed 6 weeks of overground walking using a robotic exoskeleton. The ability to walk at faster speeds with a minimal increase in metabolic cost is a promising finding, but larger sample sizes

Table 4. Adapted compendium of physical activities included MET values for exoskeleton-assisted walking overground

Activity	Group	*N*	$\dot{V}O_2$, mL/kg/min	MET_{ssci}
Exoskeleton-assisted treadmill walking (41% BWS; 100% GF)[31]	Motor-incomplete SCI	7	5.7	1.62
OG walking (slow <0.89 m/s)[4]	Noninjured adults	51	7.0	2.00*
Wheelchair propulsion outside[20]	T1-T8	14	8.0 ± 1.7	2.97
Weight training[20]	T1-T8	14	8.1 ± 2.4	2.99
Exoskeleton (Indego) walking OG (walk-1 = 0.18 m/s)	**T6-T12**	**5**	**9.5 ± 0.8**	**3.50**
Dressing/undressing[20]	T9-L4	2	10.8 ±1.8	3.99
Exoskeleton (Indego) walking OG (walk-2 = 0.27 m/s)	**T6-T12**	**5**	**11.5 ± 1.4**	**4.26**
Wheelchair propulsion on grass[20]	T1-T8	3	13.4 ± 1.6	4.96
Seated arm cycle ergometer (80 W)[20]	T1-T8	4	14.4 ± 4.2	5.34
Wheelchair basketball[20]	T1-T8	2	20.91 ± 5.53	7.74

Note: BWS = body weight support; GF = guidance force; $METs_{sci}$ = metabolic equivalent of tasks for persons with spinal cord injury; OG = overground; $\dot{V}O_2$ = oxygen consumption; W = Watts.
*MET for noninjured adults equals 3.5 mL/kg/min.

are necessary to determine whether this finding is notable or a random occurrence.

Exercise intensity can be estimated from metabolic cost and is often expressed in terms of METs, where 1 MET is equal to the energy expended during quiet sitting.[45] MET values have been used to quantify and prescribe exercise based on low (1 to 2.9 METs), moderate (3.0 to 5.9 METs), and vigorous (6.0 to 8.7 METs) intensity levels.[46] Participation in at least 150 minutes of moderate intensity or 75 minutes of vigorous intensity activity per week is recommended to lower the risk for chronic secondary health conditions such as heart disease and metabolic disorders.[46-48] Based on the above MET intensity ranges, our participant population, and the experimental conditions applied in our study, exoskeleton-assisted walking overground fell within the moderate intensity range (**Figure 1**), which suggests that, if performed with sufficient duration, potential long-term health benefits could be realized.

To our knowledge, there are no previous studies reporting the metabolic cost of exoskeleton-assisted walking overground in terms of METs. However, reports of metabolic cost of exoskeleton-assisted treadmill training provide comparisons to our findings. One study reported the metabolic cost of exoskeleton-assisted treadmill walking in METs,[31] 3 reported metabolic cost relative to $\dot{V}O_2$,[30,32,44] and one reported metabolic cost based on metabolic power calculations.[33] Based on extrapolation of $\dot{V}O_2$ data from these studies, it was possible to estimate METs based on the resting SCI MET value ($METs_{sci}$). Among these investigations, the metabolic cost of exoskeleton-assisted treadmill walking for persons with motor-incomplete SCI ranged from 1.6 to 5.2 $METs_{sci}$ depending on the percentage of body weight support, the level of assistance provided by the exoskeleton device being used, and the degree of active movement initiated by the participants. One would expect that individuals with intact lower extremity function would elicit a higher metabolic

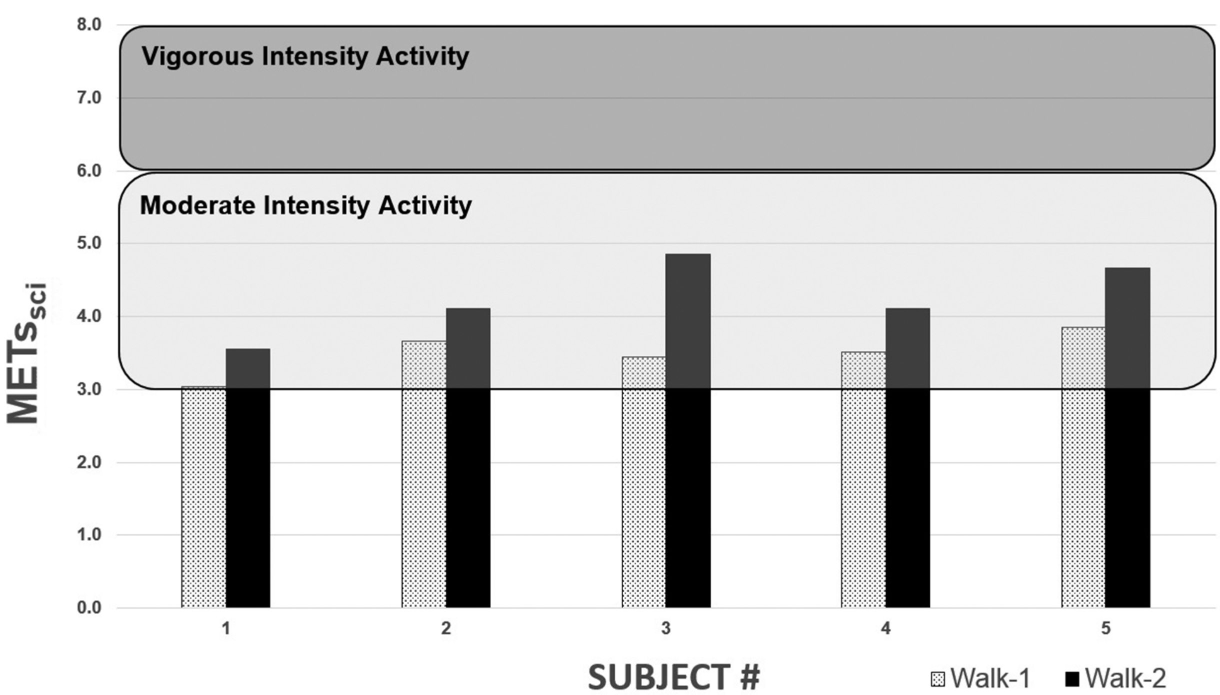

Figure 1. Metabolic equivalent of tasks (METs) during exoskeleton-assisted walking overground at 2 independent walking speeds where 1 $METs_{sci}$ is equal to the rate of energy expended while sitting at rest (2.7 mL/kg/min) as previously reported for persons with SCI.[20] Ranges for moderate (3-5.9 METs) and vigorous (≥6 METs) intensity activity have been provided based on current guidelines for physical activity and exercise intensities.[46]

demand during exoskeleton walking than persons with complete lower limb paralysis. However, in our sample population with motor-complete injury, the metabolic cost associated with exoskeleton-assisted walking overground fell within a similar range to that of treadmill walking for persons with motor-incomplete injury. One possible explanation for this finding is that, unlike exoskeleton-assisted treadmill walking, participants walking overground were required to rely upon upper extremity and possibly trunk activation to a greater extent than is required during body weight–supported treadmill training. The degree to which the upper extremities and trunk contribute to the total metabolic cost of walking overground using a robotic exoskeleton is unknown. Future research is needed to better understand the metabolic requirements associated with exoskeleton-assisted treadmill training versus exoskeleton-assisted walking overground for persons with both motor-complete and motor-incomplete SCI.

In recent years, there has been growing interest in the relationship between metabolic energy cost and changes in health outcomes following SCI.[20,49,50] Compendiums of metabolic costs have been developed with the aim of providing a basis for comparing the energy expenditures associated with various physical activities.[45] Physical activity compendiums have been compiled for nondisabled adults,[4] individuals in wheelchairs,[49] and persons with SCI.[20] **Table 4** provides comparisons of metabolic costs of exoskeleton-assisted walking overground and other physical activities. Slow walking overground (<0.89 m/s) for noninjured adults required 2 METs, whereas slow walking overground (0.18 m/s) using the Indego required 3.5 $METs_{sci}$. Faster exoskeleton-assisted walking resulted in a metabolic cost of 4.3 $METs_{sci}$, which is consistent with the METs required for noninjured adults who walk for exercise (3.8 to 5.0 METs). Given the metabolic costs of exoskeleton-assisted walking overground relative to the metabolic costs for other physical activities and exercises, there may be some potential for therapeutic benefit using this technology. However, future research is needed to determine whether long-term use of robotic exoskeleton technology can result in significant and sustained increases in metabolic activity and whether these increases can result in a meaningful therapeutic effect.

Limitations

The small sample of persons with paraplegia limits the generalizability of these results. Although individuals were instructed not to eat within 3 hours prior to testing, 2 of the 5 participants did not adhere to this request. This may have affected the resting and active metabolic rates for these individuals. However, respiratory exchange ratios were comparable to values for other participants and were within acceptable limits (≤0.90) prior to testing.

Conclusion

Persons with lower limb paralysis may be limited in their capacity to walk and perform physical exercise to the extent needed to improve health and fitness. Robotic exoskeleton devices are emerging technologies that may have utility for maintaining or improving physical conditioning and cardiorespiratory fitness following SCI. Based on preliminary data, cardiorespiratory and metabolic demands of exoskeleton-assisted walking overground are consistent with physical activities performed at a moderate intensity. Prolonged bouts of exoskeleton-assisted walking may provide a stimulus sufficient to improve cardiorespiratory fitness. Future studies are needed to investigate the training effects of walking using robotic devices.

Acknowledgments

Conflicts of interest: Shepherd Center is the lead site for US Food and Drug Administration clinical trials sponsored by Parker Hannifin Corporation (the exoskeleton device [Indego] manufacturer). As employees of Shepherd Center, C. Hartigan and C. Kandilakis have received salary support from Parker Hannifin related to their clinical research roles in the Indego clinical trials. The other authors report no conflicts of interest.

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