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Research Report

Kinematic, Muscular, and Metabolic Responses During Exoskeletal-, Elliptical-, or Therapist-Assisted Stepping in People With Incomplete Spinal Cord Injury

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Background. Robotic-assisted locomotor training has demonstrated some efficacy in individuals with neurological injury and is slowly gaining clinical acceptance. Both exoskeletal devices, which control individual joint movements, and elliptical devices, which control endpoint trajectories, have been utilized with specific patient populations and are available commercially. No studies have directly compared training efficacy or patient performance during stepping between devices.

Objective. The purpose of this study was to evaluate kinematic, electromyographic (EMG), and metabolic responses during elliptical- and exoskeletal-assisted stepping in individuals with incomplete spinal cord injury (SCI) compared with therapist-assisted stepping.

Design. A prospective, cross-sectional, repeated-measures design was used.

Methods. Participants with incomplete SCI (n=11) performed 3 separate bouts of exoskeletal-, elliptical-, or therapist-assisted stepping. Unilateral hip and knee sagittal-plane kinematics, lower-limb EMG recordings, and oxygen consumption were compared across stepping conditions and with control participants (n=10) during treadmill stepping.

Results. Exoskeletal stepping kinematics closely approximated normal gait patterns, whereas significantly greater hip and knee flexion postures were observed during elliptical-assisted stepping. Measures of kinematic variability indicated consistent patterns in control participants and during exoskeletal-assisted stepping, whereas therapist- and elliptical-assisted stepping kinematics were more variable. Despite specific differences, EMG patterns generally were similar across stepping conditions in the participants with SCI. In contrast, oxygen consumption was consistently greater during therapist-assisted stepping.

Limitations. Limitations included a small sample size, lack of ability to evaluate kinetics during stepping, unilateral EMG recordings, and sagittal-plane kinematics.

Conclusions. Despite specific differences in kinematics and EMG activity, metabolic activity was similar during stepping in each robotic device. Understanding potential differences and similarities in stepping performance with robotic assistance may be important in delivery of repeated locomotor training using robotic or therapist assistance and for consumers of robotic devices.

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Current evidence supports the use of repetitive, task-specific practice in patients with neurological injury to improve locomotor function. Gait training, or locomotor training (LT),[1,2] provided to patients with neurological injury can improve walking independence, gait speed, timed distance walking, gait efficiency, maximal aerobic capacity, and daily stepping activity.[1–5] A primary limitation of providing LT overground is the labor-intensive demands of safely supporting individuals with substantial lower-extremity weakness and simultaneously assisting stepping. Use of motorized treadmills with counterweight harness systems may increase the safety and convenience of LT while providing more precise control of body-weight support (BWS)[6] and stepping velocity.[7] Unfortunately, the physical effort required by therapists to assist stepping in patients with minimal volitional control may limit the amount of LT.[8] Despite this required effort, providing kinematic assistance during treadmill stepping in patients with reduced volitional control following stroke or spinal cord injury (SCI) can elicit muscle activity patterns associated with upright walking and may facilitate locomotor recovery.[9–11]

Various motorized, programmable (robotic) devices have been developed to facilitate LT and can be classified into 2 distinct types. Exoskeletal devices[12–14] are secured to the patient's limbs or trunk and provide constant or variable assistance at unilateral or bilateral hip and knee joints to approximate normal gait kinematics during treadmill stepping. Conversely, robotic elliptical devices[8,15,16] utilize endpoint (foot) control strategies to guide stepping movements. Selected studies have demonstrated positive outcomes using either type of robotic device, although both possess shortcomings that may limit their efficacy. For example, exoskeletal devices can closely approximate "normal" kinematics, which may be considered a positive aspect of various rehabilitation strategies.[14,17,18] However, stabilization and physical guidance of the trunk, pelvis, and lower limbs through prescribed movement trajectories can minimize movement variability,[19] which is thought to be a critical feature underlying motor learning.[18] Providing such assistance also may reduce the muscular and metabolic demands associated with stepping.[20] During repeated LT, increased muscle activity appropriate for the biomechanical subtasks of walking (eg, limb swing or propulsion) and increased metabolic activity during LT are thought to be critical features that facilitate improvements in walking recovery. Alternatively, these constraints may augment specific muscle activity during portions of the gait cycle when such activity would be unwanted. Specifically, selected devices utilize elastic straps at the forefoot to aid dorsiflexion during limb swing, which may increase plantar pressure and plantar-flexor stretch and contribute to increased extensor electromyograpic (EMG) activity during swing.[20] These combined limitations in patient performance during exoskeletal-assisted stepping were postulated to contribute to the reduced efficacy of repeated LT using this device compared with therapist-assisted LT.[21]

In contrast, elliptical devices represent a control strategy that also could facilitate walking improvements, although this strategy may possess similar limitations. Consistent with exoskeletal devices, elliptical assistance also may reduce volitional activity, and continuous plantar pressure on the footplates may provide stimuli associated with limb loading during swing. However, single endpoint control of limb movements represents a simpler design, which could allow more variability of joint kinematics during stepping practice by minimizing stabilization of the pelvis and lower limbs. Alternatively, the lack of kinematic constraints may lead to abnormal gait kinematics, which has been thought by other investigators to impair restoration of normal walking patterns.[8,17,18] Recent data suggest that hip and knee angular excursions of individuals without neurological injury during elliptical stepping are slightly flexed compared with overground walking,[22] although this has not been established in patients with neurological injury.

Despite the limitations of both locomotor control strategies, the reduced therapist effort afforded by either device may increase delivery of LT in individuals with substantial weakness but emerging recovery of strength early following neurological injury. Such training provided soon after injury may facilitate greater gains in walking function.[23] Questions remain as to what control strategies optimize locomotor recovery. Previous investigations have focused on evaluation of patient performance (ie, gait kinematics, muscle

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- eTable 1: Kinematic Excursions and Measures of Variability in Participants Without Neurological or Orthopedic Injury and in Participants With Incomplete SCI
- eTable 2: Muscle Activity Patterns in Participants Without Neurological or Orthopedic Injury and in Participants With Incomplete SCI
- eTable 3: Spearman Correlation Coefficients for Stepping Performance Variables and Lower Extremity Motor Score for Individuals With Incomplete SCI

activity patterns, and metabolic cost of stepping) with either device compared with overground or treadmill stepping.[20,22] However, no studies have compared differences between devices in individuals with neurological impairments (see Regnaux et al[24] for a single-subject comparison).[3]

The primary goals of this study were to evaluate kinematic, EMG, and metabolic responses of individuals with incomplete SCI (iSCI) during therapist-, exoskeletal-, and elliptical-assisted stepping. Consistent with previous data,[19–21] substantial differences in performance variables favoring one stepping condition over another may provide insight into the potential efficacy of training paradigms and provide an argument for preferentially utilizing one method of assistance. In contrast, if performance variables are not different across stepping conditions, other factors such as the number of therapists required to provide stepping training or the cost of the device may facilitate selective utilization of these devices in the clinical setting.

In the current study, we hypothesized that therapist-assisted stepping would result in greater metabolic costs and more appropriate muscle activation patterns than either robotic LT device, with few differences between devices. We further anticipated greater hip and knee flexion and greater kinematic variability with elliptical-assisted stepping, although kinematic trajectories evaluated during exoskeletal-assisted stepping would mimic those of individuals without neurological injury. Despite these kinematic differences, we anticipated that the metabolic and muscular behaviors would be similar for each stepping device, but inferior to therapist-assisted stepping as needed. Evaluation of stepping performance with different robotic devices may generate hypotheses about their potential efficacy during repeated LT.[25]

Method

Participants

Potential research participants with iSCI were recruited from the outpatient clinics of the Rehabilitation Institute of Chicago. Individuals were classified by the American Spinal Injury Association (ASIA) Impairment Scale (AIS)[26] as C or D, indicating motor incomplete lesions. Additional inclusion criteria were: participant age between 18 and 75 years, history of iSCI >6 months, neurological lesion level higher than T10, and lower-extremity passive range of motion (ROM) consistent with upright human locomotion. Exclusion criteria were: concurrent illness that might limit exercise or walking performance, including unhealed decubiti, substantial cardiopulmonary or metabolic disease, history of osteoporosis, active heterotopic ossification, or other peripheral or central neurological injury, and inability to tolerate upright positions for 30 minutes. Ten participants without neurological or orthopedic injury (5 men and 5 women, age range=25–41 years) also were recruited to evaluate normative EMG responses and kinematics during unassisted treadmill stepping. Each

The Bottom Line

What do we already know about this topic?

Robotic devices have the potential to alleviate the physical labor of therapists during the gait training of patients with severe motor deficits following neurological injury. Many robotic devices have been developed and tested; some devices, such as exoskeletal devices, control individual joint motion, whereas other devices, such as elliptical devices, control only the end-point (ie, foot) trajectories. These devices can vary in their control strategies, complexity, and costs; however, no studies have directly compared these different types of devices.

What new information does this study offer?

This study provides a physiological rationale for understanding the potential differences between exoskeletal and elliptical devices. It found few differences between the devices in terms of joint kinematics, muscle activity patterns, and metabolic cost of walking. The physiological basis for use of one device versus another, therefore, may not be warranted. Although further randomized trials are forthcoming, the use of the costly and complex exoskeletal devices might not be necessary, because the end-point control strategies of elliptical devices may provide equivalent outcomes.

If you're a patient or a caregiver, what might these findings mean for you?

Although patients with severe motor deficits following neurological injury could benefit from using either an exoskeletal device or an elliptical device for locomotor training, the lower costs and the simplicity of elliptical devices mean that these devices may be more common in rehabilitation facilities.

participant provided written informed consent prior to the study.

Clinical examination included assessment of lower-extremity strength and walking ability using reliable and valid outcome measures in this patient population. Strength was determined using the ASIA Lower Extremity Motor Score (LEMS).[27] The Walking Index for Spinal Cord Injury II (WISCI II)[28] was used to evaluate the use of braces, assistive devices, and therapist assistance during overground walking. If participants with iSCI could ambulate without assistance, preferred overground gait speed was determined using the GaitMat II (EQ Inc, Chalfont, Pennsylvania).[29]

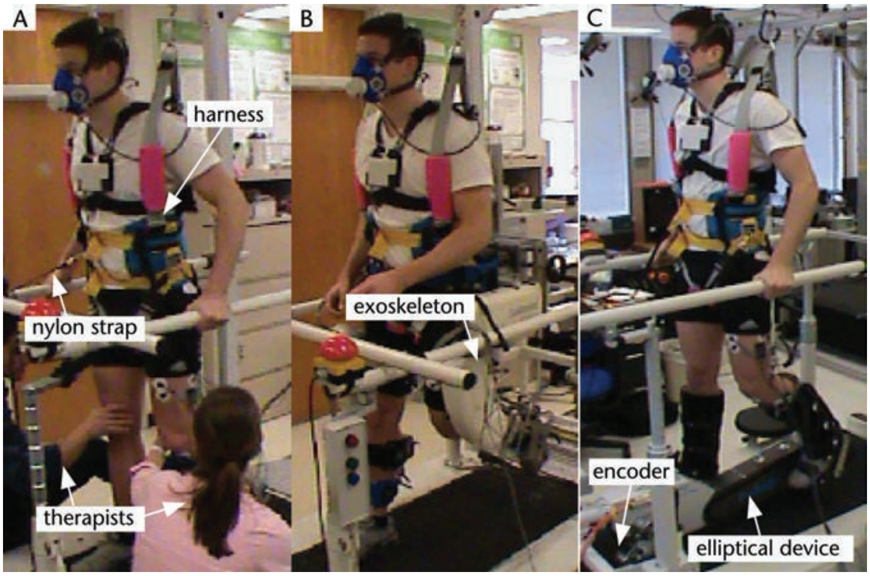

Figure 1.
Experimental setup for kinematic, electromyographic, and metabolic data collection during therapist-assisted stepping (A), exoskeletal-assisted stepping (B), and elliptical-assisted stepping (C).

Experimental Design

A repeated-measures experimental design was used to assess the biomechanical and physiological responses to therapist-assisted treadmill stepping, robotic exoskeletal stepping, and robotic elliptical stepping in participants with iSCI. Comparisons between kinematics and EMG activity of participants without injury during treadmill stepping and data collected in participants with iSCI during each stepping condition also were made.

Instrumentation

The equipment and details of the experimental setup for therapist-, exoskeletal- and elliptical-assisted stepping have been described previously[8,20] (Fig. 1). During all testing, participants were secured over a motorized treadmill with a harness-counterweight support system (Woodway GmbH, Weil am Rhein, Germany). Participants were allowed to use the bilateral handrails to maintain postural stability, although they were asked to minimize upper-extremity weight bearing.

During therapist-assisted stepping, manual assistance was provided by up to 2 therapists (1 at each leg) as needed to advance the limbs during swing or to provide knee extension in stance.[21] Trunk and pelvic stabilization was provided as needed by nylon straps attached to the harness directly above the waist and anteriorly to the treadmill handrails. The straps were removed if patients could maintain pelvic stability independently during treadmill stepping. Participants with iSCI were allowed to wear their customary ankle-foot orthosis as necessary.

During exoskeletal stepping, participants were positioned in an exoskeletal robotic orthosis (Lokomat, Hocoma AG, Zurich, Switzerland) as described previously.[20] The harness was secured to the orthosis at the pelvis and trunk, with lateral and posterior pads limiting pelvic movement in all planes. Bilateral hip and knee joints were aligned with the orthotic joint axes, and the device was secured to participants with thigh, shank, and waist straps. For testing purposes, the knee joint was aligned slightly anterior to the robotic knee axis to minimize knee hyperextension. Elastic straps attached to the orthosis and the participant's forefoot were used to assist dorsiflexion during swing. If participants demonstrated sufficient volitional dorsiflexion, no elastic straps were used. Sagittal-plane gait kinematics similar to upright human locomotion were automated by linear actuators at bilateral hip and knee joints programmed to guide symmetrical stepping patterns timed to the treadmill speed.

Elliptical-assisted stepping was performed using the Pedago (Lokohelp, Zlin, Czech Republic), an automated, elliptical training device that is secured to the treadmill frame and operates in conjunction with the treadmill.[8] A servomotor drives the elliptical device in a fixed trajectory (0.5-m step length), and an encoder matches the speed of the elliptical device movement to the treadmill speed. Participants' feet were secured in long, rigid boots extending below the knee, which were attached to the levers extending laterally from the device. Motion of the ankle was constrained, although the boots could rotate about the levers in the sagittal plane. Pelvic and trunk support was provided as necessary via nylon straps attached to the harness and treadmill handrails (4 participants total), similar to therapist-assisted stepping.

Hip and knee kinematics and surface EMG recordings were collected on the left limb in all participants. Joint kinematics were estimated using electrogoniometers (Delsys Inc, Boston, Massachusetts) secured across the hip and knee joints and calibrated (>3 joint angles throughout the available ROM) prior to each testing condition to account for movement between protocols. Footswitches (Noraxon USA Inc, Scottsdale, Arizona) were placed on the forefoot and toes and the hindfoot (minimum of 4 footswitches) to estimate the timing of unilateral stance and swing gait phases. Electromyographic recordings were obtained from the tibialis anterior (TA), soleus (SOL), medial gastrocnemius (MG), vastus lateralis (VL), rectus femoris (RF), and medial hamstring (MH) muscles using adhesive Ag-AgCl electrodes (ConMed Corp, Utica, New York) and a commercial EMG system (Noraxon USA Inc). The EMG signals were amplified (10×) and band-pass filtered at 10 to 500 Hz.

Oxygen consumption ($\dot{V}O_2$; mL/kg/min) was determined using a portable metabolic system (CosMed USA Inc, Chicago, Illinois) calibrated prior to testing using room air and a reference gas mixture (16% oxygen and 5% carbon dioxide). Metabolic data were collected on a breath-by-breath basis and stored for subsequent analysis.

Procedure

All participants with SCI were familiarized to stepping in each device for 2 to 4 minutes prior to testing. Resting $\dot{V}O_2$ measurements were collected while sitting for 2 minutes prior to each testing condition. Participants then were instrumented in each device with 40% BWS, and 6 minutes of continuous stepping was performed. Treadmill speed was set at 1.5 kmph (0.42 m/s). This speed is below published recommendations for LT,[1] but was chosen to accommodate the degree of motor impairments and the physical assistance required to facilitate continuous stepping for 6 minutes. Further exoskeletal- and elliptical-assisted stepping was performed in the passive mode of operation to minimize differences across testing conditions. Auditory cues using a metronome were used to ensure similar cadences (44 steps/min), which were fixed in the elliptical device at this speed. During exoskeletal-assisted stepping, hip and knee kinematics were adjusted to standard settings, with the hip kinematics readjusted to ensure cadences similar to those of elliptical-assisted stepping. Stepping kinematics and EMG data also were collected on 10 participants without injury during treadmill stepping at the same speed and cadence assessed in participants with iSCI.

Throughout testing, participants with iSCI were provided initial instructions to generate the maximal effort required to perform continuous stepping. Verbal encouragement was provided throughout testing to maximize participant effort, although no additional feedback was provided. No additional therapist assistance was provided during elliptical- or exoskeletal-assisted stepping. After each 6-minute bout of walking, participants rested for >20 minutes.

Data Analysis

Kinematic, EMG, and footswitch data were sampled at 1,000 Hz during the final 30 seconds of the last 3 minutes of each testing bout using a custom-designed MatLab (The MathWorks Inc, Natick, Massachusetts) program. Footswitch data were utilized to estimate stance and swing phases during exoskeletal- and therapist-assisted stepping on the treadmill surface. During elliptical testing, plantar pressure during the apparent swing phase of the gait cycle was sufficient to intermittently activate footswitches and could not be used to detect gait transitions. Instead, gait transitions were estimated using hip kinematics. Specifically, during treadmill walking in participants without neurological injury, gait transitions are associated with a rapid change in hip excursion from peak flexion toward extension (swing-stance) and peak extension toward flexion (stance-swing). Accordingly, early stance (initial contact) was estimated as the transition from peak hip flexion toward extension, and swing initiation was determined as the transition from peak hip extension to flexion.

Primary kinematic measures included peak swing-phase hip and knee flexion, peak stance-phase hip and knee extension, and total joint ROM during stepping. We evaluated intralimb consistency of the hip-knee kinematics using the average coefficient of correlation (ACC).[30,31] The ACC uses a vector coding technique to estimate the consistency of sagittal-plane hip-knee angles throughout the normalized gait cycle using angle-angle plots. For each 1% of the gait cycle, the change in hip-knee angles on the phase plane was represented by a vector, whose length and direction were determined using the following equations:

(1) $$l_i = \sqrt{x_i^2 + y_i^2}$$

(2) $$cos\theta_i = \frac{x_i}{l_i}$$

(3) $$sin\theta_i = \frac{y_i}{l_i}$$

where x_i and y_i are the change in the hip and knee angle from frame i to $i+1$ and l_i is the length of that vector. The mean cosθ and sinθ for a given frame (percentage of the gait cycle) over multiple gait cycles then were determined. The correlation coefficient (a_i) for each frame was evaluated by the following equation:

$$(4) \quad a_i = \sqrt{cos\bar{\theta}\frac{2}{i} + sin\bar{\theta}\frac{2}{i}}$$

where cos$\bar{\theta}_i$ and sin$\bar{\theta}_i$ are the mean cosθ and sinθ for each i frame. Values of a_i were used as the measure of dispersion across gait cycles of the hip and knee angles at each percentage of the gait cycle. All a_i values were represented as a single variable by calculating the mean correlation coefficient (ACC) for all i frames. Perfectly consistent hip-knee trajectories across all gait cycles generate an ACC value of 1.0 (no units), and no consistency provides a value of 0.0.

Electromyographic signals were filtered using a fourth-order recursive Butterworth filter (band-pass 30–450 Hz, band-stop 58–62 Hz) and full-wave rectified. Linear envelopes of the filtered, rectified EMG signal were created using a 20-Hz low-pass filter (fourth-order recursive Butterworth). Electromyographic activity was normalized to percentage of the gait cycle. Differences in EMG amplitudes and timing during stepping conditions were determined using a variation of the Spastic Locomotor Disorder Index (SLDI),[32] which evaluated timing of EMG responses relative to normative data, determined from 10 participants without neurological injury. Normative data were first evaluated to determine periods of consistent EMG during the gait cycle ("on" periods) versus periods without muscle activity ("off" periods), with each "on" period provided as a percentage of the gait cycle: TA: 0%–15%, 65%–100%; MG: 5%–55%; SOL: 5%–55%; RF: 0%–25%, 50%–75%, 95%–100%; VL: 0%–25%, 50%–75%, 95%–100%; MH: 0%–25%, 65%–100%. "On" periods were consistent with published data,[33] with the exception of VL activity during 50% to 75% of the gait cycle (see "Results" section). Using these data, the SLDI was calculated as the ratio of rectified EMG area during the "off" periods for each muscle to the area during the "on" periods, where lower SLDI values indicate normal timing. Because electrodes were not removed throughout testing of participants with iSCI, EMG data during "on" and "off" periods also were compared among stepping conditions. Comparison between participants without injury during treadmill walking and those with iSCI during all conditions were limited to SLDI values.

Measurements of $\dot{V}O_2$ were averaged across 1-minute intervals during each stepping condition, with steady-state $\dot{V}O_2$ calculated from mean data over minutes 4 to 6. Baseline metabolic values from quiet sitting were subtracted from walking $\dot{V}O_2$ measurements.

Primary statistical analysis focused on differences in kinematic, EMG, and metabolic parameters in participants with SCI during each stepping condition using one-way repeated-measures analyses of variance, with *post hoc* Tukey-Kramer tests used if differences were significant (α=.05). In addition, separate unpaired comparisons (t tests) of kinematics and EMG activity (SDLI only) were made between participants with iSCI during the different stepping conditions and participants without injury during treadmill stepping.

Secondary analyses focused on associations between stepping performance of participants with iSCI in each robotic device and their clinical characteristics, including LEMS and WISCI scores and duration postinjury. As LEMS and WISCI scores were significantly correlated (Spearman rho=.91) and associations with LEMS were greater, only correlations with LEMS are detailed. Furthermore, because of the difficulty in comparing absolute metabolic and EMG activity across participants, metabolic and EMG responses ("on" area) during stepping with either type of robotic device were normalized to (divided by) data collected during therapist-assisted stepping. In contrast, absolute knee and hip angular excursions were utilized and compared across robotic-assisted stepping conditions. Parametric and nonparametric (Spearman) correlation analyses were performed as appropriate. Statistical calculations were performed using SPSS version 15 (SPSS Inc, Chicago, Illinois).

Role of the Funding Source

The study was funded by the National Institute of Disability and Rehabilitation Research (H133N060014). The elliptical device was provided by the manufacturers for evaluation free of charge. Neither source played a role in study design, data collection and analysis, or interpretation.

Results

Eleven individuals with iSCI participated in the present study. In 1 participant, the hip electrogoniometer was detached during exoskeletal stepping and, in another participant, EMG activity was not collected during treadmill stepping. Hip kinematics and EMG activity data, therefore, were analyzed from 10 participants with iSCI, with knee kinematics and $\dot{V}O_2$ data available from all 11 participants with iSCI. Ten of these participants had previous experience with therapist-assisted stepping, 9 had previous experience with exoskeletal stepping, and 4 had previous experience with elliptical stepping.

Table.

Participants' Clinical Characteristics and Demographics: Age, Level of Injury (LOI), American Spinal Injury Association Impairment Scale (AIS) Classification, Duration of Injury (DOI), Lower Extremity Motor Score (LEMS), Walking Speed, Walking Index for Spinal Cord Injury-II (WISCI II) Score, Ankle-Foot Orthosis (AFO) Use During Stepping With Therapist Assistance, and Number of Physical Therapists Required to Assist During Therapist-Assisted Stepping

Participant No.	Age (y)	LOI	AIS Classification	DOI (mo)	LEMS	Walking Speed (m/s)	WISCI II Score	AFO Use During Stepping	No. of Physical Therapists Required
1	18	C4–C6	C	20	8		0	Yes	2
2	30	C7	D	44	24	0.24	9	No	1
3	27	C5–C8	C	20	4		0	Yes	2
4	50	C2–C3	D	28	45	0.52	13	No	0
5	31	T3	C	51	18	0.08	9	Yes	1
6	41	T1	C	220	16		6	Yes	2
7	61	T7	C	367	21	0.10	9	Yes	1
8	43	C5	C	84	9		0	Yes	2
9	19	T6–T7	C	25	21	0.16	9	Yes	1
10	47	C5–C6	D	276	42	0.74	19	No	0
11	62	C4	D	80	36	0.50	19	No	0

Kinematics and EMG activity of the participants with iSCI were compared against those of 10 participants without injury during treadmill walking. Clinical characteristics of the participants with iSCI are provided in the Table, indicating reduced overground walking speeds with use of assistive devices or bracing or no independent walking ability. Data on use of an ankle-foot orthosis and number of therapists required during therapist-assisted stepping also are provided.

Kinematic Parameters

Gait kinematics collected during therapist-, exoskeletal-, and elliptical-assisted stepping in participants with iSCI revealed significant differences across testing conditions and compared with participants without injury during treadmill stepping. Data from a single participant with iSCI are provided in Figure 2A, along with averaged kinematic data for participants without injury. All kinematic data are provided in eTable 1 (available at ptjournal.apta.org).

Comparison of hip excursions revealed more flexed postures in participants with iSCI in all stepping conditions compared with participants without injury, with 6.5 to 16 degrees (mean range) greater swing-phase flexion and 7.1 to 22 degrees less stance-phase extension. Significant differences from participants without injury were observed in participants with iSCI only during elliptical stepping for peak hip flexion and extension (both P=.03; eTab. 1). Comparisons among participants with incomplete SCI indicated that all hip kinematic variables were statistically different (Fig. 2C). *Post hoc* assessments revealed greater swing-phase hip flexion during elliptical-assisted versus therapist-assisted versus exoskeletal-assisted stepping and less stance-phase extension during elliptical-assisted versus exoskeletal-assisted stepping. Hip ROM during stepping also was greater during elliptical- and therapist-assisted stepping versus exoskeletal-assisted stepping.

Knee kinematic data also revealed more flexed postures in participants with iSCI during all stepping conditions compared with participants without injury, with 14 to 21 degrees increased swing-phase knee flexion and 8.1 to 14 degrees decreased stance-phase knee extension. Significant differences in knee flexion were observed between participants with iSCI and those without injury across all stepping conditions, whereas peak knee extension in participants with iSCI was different from that of participants without injury only during exoskeletal-assisted stepping. Comparisons among different stepping conditions revealed nonsignificant (~10°) differences for peak knee flexion and extension (Fig. 2D), although total knee ROM was greater during elliptical- versus exoskeletal-assisted stepping.

Evaluation of intralimb kinematic variability using the ACC also revealed differences across stepping conditions and between participant groups. Single-subject hip-knee angle-angle plots and grouped data during the 3 testing conditions are provided in Figures 2E and 2F. Average data indicate that the largest ACC values occurred during exoskeletal-assisted stepping (eTab. 1) and were consistent with ACC values of participants without neurological injury. In contrast, ACC values during therapist- and elliptical-assisted stepping were similar to each other but lower than in exoskeletal-assisted stepping. Significant differences were observed only between exoskeletal- and therapist-assisted stepping.

EMG Measurements

Muscle activity patterns were analyzed for each of the 3 conditions, with representative data from a single participant with iSCI shown in Figure 3. Shaded areas represent the timing of normative EMG data collected from the control participants. Grouped data of "on" and "off" muscle activity periods across participants in each of the stepping conditions are provided in eTable 2 (available at ptjournal.apta.org). Lower SLDI values were observed for nearly all muscle groups in participants without injury compared with those with iSCI regardless of stepping conditions, with significant differences observed only for the lower leg muscles under specific conditions (eTab. 2).

Despite the single-subject differences in TA and SOL activity shown in Figure 3, comparisons across participants with iSCI during different stepping conditions revealed no significant differences in these muscles. No differences in MG EMG activity were observed during the stance ("on") phase (5%–55% of the gait cycle; P=.30), although increased abnormal EMG activity was observed during the swing phase (P=.04). *Post hoc* assessments revealed significantly greater activity during exoskeletal-assisted stepping versus elliptical- and therapist-assisted stepping.

For the quadriceps muscles, increased RF EMG activity was observed during both 25% to 50% of the gait cycle ("off" period) and 50% to 75% of the gait cycle ("on" period; P<.05) during elliptical-assisted stepping, with *post hoc* assessments indicating approximately 160% greater activity compared with exoskeletal-assisted stepping during 50% to 75% of the gait cycle (P=.04). For both the VL (P=.01) and RF (P=.05), greater muscle activity was observed during 25% to 50% of the gait cycle ("off" period) during therapist- versus exoskeletal-assisted stepping, with further differences for the VL during 50% to 75% of the gait cycle (P=.01)

Finally, significant differences were observed in MH EMG activity during

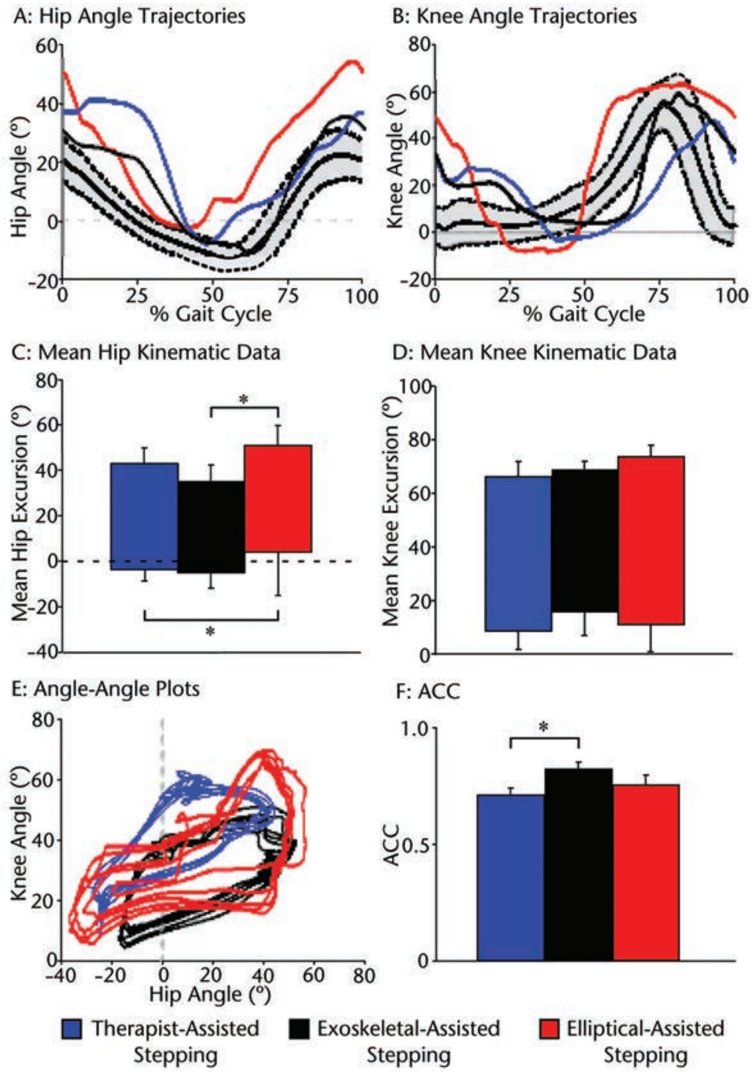

Figure 2.
Single-subject sagittal-plane hip (A) and knee (B) kinematics during therapist-assisted stepping (blue), exoskeletal-assisted stepping (black), and elliptical-assisted stepping (red) averaged over more than 20 gait cycles and normalized to percentage of the gait cycle. Normative data provided in dark gray, with standard deviation in light shaded gray. Average angular excursions for hip (C) and knee (D) kinematics are provided (error bars=standard errors), with asterisk indicating significant *post hoc* Tukey-Kramer differences. Single-subject hip-knee angle-angle plots during therapist-, exoskeletal-, and ellipitical-assisted stepping (E), with average coefficient of correlation (ACC) values (F) provided (significance indicated by asterisk).

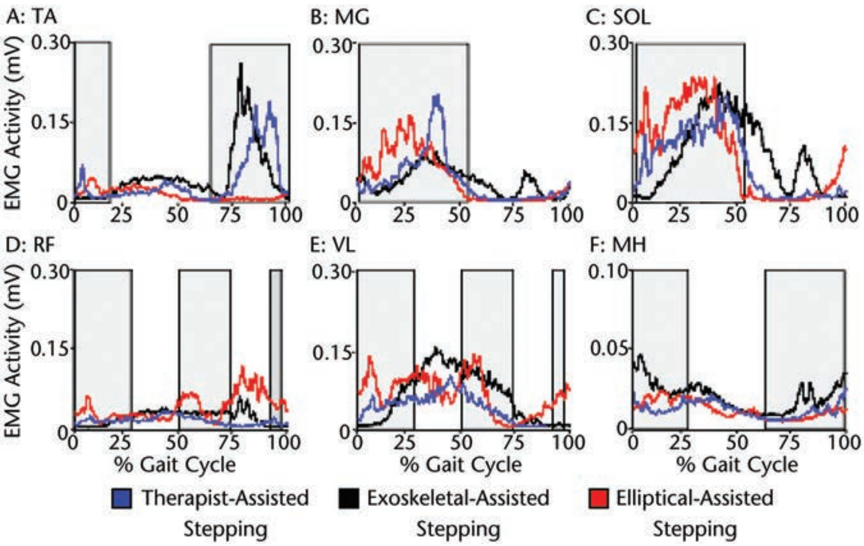

Figure 3.
Rectified, filtered, single-subject electromyographic (EMG) activity for the (A) tibialis anterior (TA), (B) medial gastrocnemius (MG), (C) soleus (SOL), (D) rectus femoris (RF), (E) vastus lateralis (VL), and (F) medial hamstring (MH) muscles recorded during therapist-assisted stepping (blue), exoskeletal-assisted stepping (black), and elliptical-assisted stepping (red). Data were averaged over more than 20 gait cycles and normalized to percentage of the gait cycle. Shaded areas indicate periods of normative EMG activity evaluated in 10 participants without neurological injury.

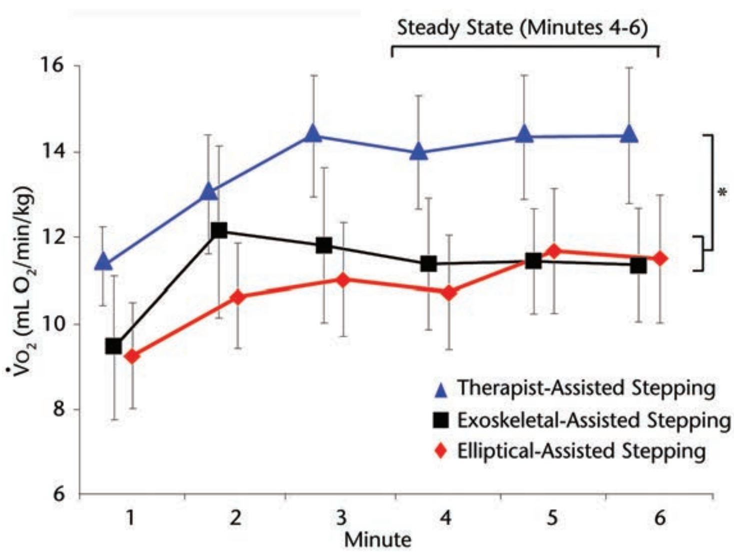

Figure 4.
Grouped averages of oxygen consumption ($\dot{V}O_2$) during each 6-minute bout of therapist-assisted stepping (blue), exoskeletal-assisted stepping (black), and elliptical-assisted stepping (red). Data were averaged over each minute. Asterisk indicated significant *post hoc* Tukey-Kramer differences.

the "on" phase (65%–100% of the gait cycle; P=.01), with *post hoc* analyses revealing 3-fold greater activity during exoskeletal- versus elliptical-assisted stepping.

Metabolic Parameters

Analysis of metabolic responses in individuals with SCI revealed marked differences across stepping conditions (Fig. 4). Average peak $\dot{V}O_2$ during therapist-assisted stepping was 19.7% (SD=9.4%) and 19.8% (SD=10.2%) greater than peak $\dot{V}O_2$ observed during elliptical- and exoskeletal-assisted stepping, respectively (P<.01), with no differences between these stepping conditions and robotic-assisted stepping.

Association Between Stepping Performance and Clinical Characteristics

Potential associations between clinical characteristics (LEMS, duration post-SCI) and stepping performance (gait kinematics, EMG activity, $\dot{V}O_2$) were determined during robotic-assisted stepping (as normalized to therapist-assisted stepping condition). There were no significant correlations between duration post-SCI and any stepping performance variable. In contrast, significant correlations between LEMS and stepping performance variables were observed, with specific relationships provided in Figure 5 (all coefficients are shown in eTab. 3, available at ptjournal.apta.org). For gait kinematics, LEMS were not well correlated with hip kinematics (eg, peak hip flexion versus LEMS; Fig. 5A), with larger but negative correlation coefficients demonstrated for knee kinematics (eg, peak knee extension versus LEMS, Fig. 5B). Significant correlations, however, were observed only between LEMS and peak knee flexion during exoskeletal-assisted stepping.

Positive correlations also were observed between LEMS and selected measures of EMG and metabolic activity, and relationships were significant only during elliptical-assisted stepping conditions. Figure 5C demonstrates the moderate correlation between LEMS and RF activity ("on" area) during elliptical stepping, with minimal correlation during exoskeletal-assisted stepping. Similar findings were observed for the VL and MG (eTab. 3). Similarly, $\dot{V}O_2$ was significantly related to LEMS for elliptical-assisted stepping but not exoskeletal-assisted stepping (Fig. 5D).

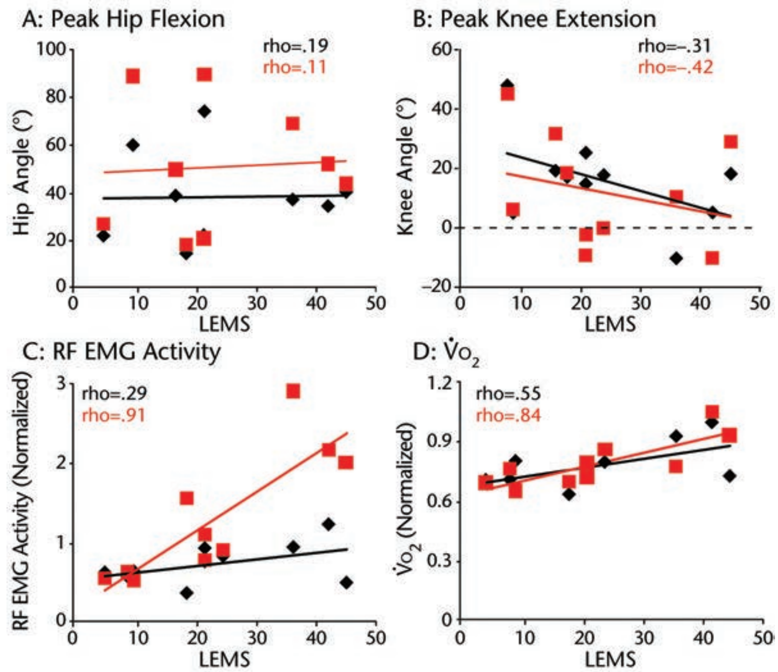

Figure 5.
Associations between Lower Extremity Motor Score (LEMS) and (A) peak hip flexion (P=.48 for exoskeletal-assisted stepping, P=.65 for elliptical-assisted stepping), (B) peak knee extension (P=.14 for exoskeletal-assisted stepping, P=.11 for elliptical-assisted stepping), (C) rectus femoris muscle (RF) electroyographic (EMG) activity during "on" period (P=.42 for exoskeletal-assisted stepping, P<.01 for elliptical-assisted stepping), and (D) oxygen consumption ($\dot{V}O_2$) (P=.13 for exoskeletal-assisted stepping, P=.02 for elliptical-assisted stepping). Black=therapist-assisted stepping minus exoskeletal-assisted stepping, red=therapist-assisted stepping minus elliptical-assisted stepping.

Discussion

Direct comparison of the efficacy of robotic- and therapist-assisted LT may provide clinicians with quantitative data to help determine which training paradigms may be most appropriate for their patient population. In the absence of such data, evaluation of physiological and biomechanical variables during stepping with different devices may provide insight into how patients would respond to such interventions. Previous studies evaluating differences in metabolic costs and EMG patterns during therapist- and exoskeletal-assisted stepping provided potential insight into how patients with neurological injury responded to repeated LT using these paradigms (for example, see Israel et al[20]).

Differences in Kinematic Parameters

Evaluation of kinematic behaviors in participants with iSCI revealed generally increased hip and knee flexion compared with those of participants without injury, although greater hip flexion postures were observed with elliptical-assisted stepping. These findings were anticipated in light of a recent investigation detailing kinematic behaviors in individuals without neurological injury during elliptical stepping.[22] Using 4 commercial devices, hip and knee flexion were increased approximately 15 and 10 degrees, respectively, during mid-swing compared with overground walking, with smaller differences (<10°) during stance. Although the degree of hip and knee flexion observed in participants with iSCI in the present investigation was greater than that observed previously in individuals without neurological injury, greater knee flexion postures may be related to the reduced volitional strength of this patient population (Fig. 5B), regardless of the device used.

Differences in kinematic consistency (ACC) across assisted stepping conditions also were observed and anticipated based on previous data. In particular, ACC values observed in participants with iSCI during exoskeletal-assisted stepping, where kinematics were precisely controlled,[34] were high and closely resembled those of participants without neurological injury during unassisted stepping. Although therapist-assisted stepping may be able to more closely approximate normal kinematics than demonstrated in this study, selected participants with iSCI could step without substantial assistance, and no corrections were made by the assisting therapists to normalize stepping patterns. Providing such assistance as needed to other participants likely varied on a step-by-step basis, which also could account for the lower ACC values. Elliptical-assisted stepping also demonstrated substantial variability in intralimb coordination similar to therapist-assisted conditions, where control of endpoint kinematics can allow individuals to explore different hip and knee kinematic configurations. The combined results suggest substantial variations between robotic-assisted stepping paradigms dependent on the control strategy used, with similarities between kinematics of the participants with iSCI during exoskeletal-assisted stepping and control participants, and between therapist- and elliptical-assisted stepping conditions.

The practice of kinematically correct movement patterns during training traditionally has been viewed as a desired strategy of rehabilitation interventions,[8,17,18] which can be provided by exoskeletal devices. However, previous studies that have evaluated gait-related changes following exoskeletal-assisted LT, particularly those that provided precise control of joint kinematics, indicated very few alterations in spatiotemporal kinematics[21] or joint kinematics,[19,35] particularly compared with unconstrained practice or therapist-assistance as needed. Rather, training strategies characterized by greater variability of movement patterns while still approximating normal stepping patterns as performed with therapist-assisted LT resulted in larger improvements in spatiotemporal and kinematic consistency (ACC values) and performance[19] following completion of training. Although there is little knowledge of what the optimal variability of stepping would be to facilitate stepping recovery in patient populations, elliptical-assisted stepping appeared to approximate gait kinematics and consistency similar to those observed with therapist-assisted stepping. Despite these similarities, a concern regarding providing elliptical-assisted stepping may be the demonstration of increased hip flexion and reduced extension, which theoretically could be reinforced during repeated LT with elliptical assistance. However, previous LT studies using elliptical devices have not reported whether such behaviors were observed following training.[16,36]

Differences in EMG Activity

Selective alterations in EMG amplitude and timing were observed across stepping conditions. Increased swing-phase MG activity during exoskeletal-assisted stepping was demonstrated (also see Israel et al[20]), which may be due to increased plantar pressure and plantar-flexion stretch provided with elastic straps to assist dorsiflexion.[37,38] However, swing-phase MG activity was not significantly greater during elliptical-assisted stepping despite presumed continuous plantar pressure. The extent of plantar pressure and plantar-flexor stretch present during exoskeletal-assisted stepping was not clear in the present study, although future assessment of forces and pressures and of ankle kinematics could help elucidate their contribution to altered MG activity. Conversely, increased MG activity but not SOL activity may represent increased volitional effort during swing phase knee flexion, as MH activity also was increased in the swing phase during exoskeletal-assisted stepping.[39] However, knee flexors typically act eccentrically during swing to minimize knee extension prior to initial contact, and the increased MH and MG activity may represent increasing muscle stretch with passive knee extension.

For upper leg (thigh) muscles, there also were selective differences in muscle activity patterns between groups. Quadriceps muscle activity was significantly different across stepping conditions in participants with SCI in previous studies,[20,39] with increased activity in mid-stance and stance-swing transitions (25%–75% of the gait cycle) during therapist- or elliptical-assisted stepping compared with exoskeletal-assisted stepping. Increased quadriceps muscle EMG activity during 25% to 50% of the gait cycle is not normally observed in participants without neurological injury during unassisted stepping and would generally be considered aberrant muscle activity. However, increased quadriceps muscle activity during elliptical- and therapist-assisted stepping may have been necessary to maintain upright (extended) limb postures without exoskeletal bracing about the knee. The positive correlation between quadriceps muscle EMG activity and LEMS during elliptical stepping may indicate increased volitional effort to maintain greater extension for those with sufficient strength. Regardless, increased quadriceps muscle activity during stance was observed in therapist- and elliptical-assisted stepping conditions, and increased MG and MH activity was observed in exoskeletal-assisted stepping during swing.

Differences in Metabolic Parameters

Although $\dot{V}O_2$ is considered a measure of demands on the cardiovascular system to deliver oxygen to working muscles during aerobic tasks,[4] evaluation of $\dot{V}O_2$ also provides an estimate of the rate of continuous muscular activity during these tasks. Previous studies performed on individuals without neurological injury demonstrated the potential contributions of various biomechanical subtasks of upright locomotion to the overall cost of walking (ie, upright stance,[40] propulsion,[41] limb swing,[42] lateral stability[43]) by providing assistance for these tasks and simultaneously investigating the changes in $\dot{V}O_2$ and EMG activity. As evaluation of EMG activity from all muscles subserving upright walking is difficult if not impossible, evaluation of $\dot{V}O_2$ in these studies provided a more global estimate of how biomechanical assistance may alter the muscular requirements of a locomotor task.

In the present study, we believe the observation of differences in $\dot{V}O_2$ responses of approximately 20% during therapist- versus either robotic-assisted stepping condition likely reflected reduced muscle activity. Such differences may have been due, in part, to differences in quadriceps muscle activity between tasks, although other factors might have contributed. One explanation may be the lack of feedback provided during robotic-assisted stepping, as previous data indicated nearly equivalent $\dot{V}O_2$ between therapist- and exoskeletal-assisted stepping with provision of external feedback of lower-limb forces.[20] Reduced $\dot{V}O_2$ also could be accounted for by the biomechanical constraints provided during robotic-assisted stepping,[41–43] including the assistance provided by these devices. Although the precise reasons for the observed differences are not clear, increased metabolic (ie, aerobic) demands during LT have been considered an important component of selective LT paradigms.[4,44,45] Reducing the metabolic demands during LT may subsequently reduce the gains in locomotor performance, which was postulated to contribute to greater walking-related gains following therapist- versus exoskeletal-assisted LT in individuals poststroke.[21]

Given the combined differences and similarities in patient performance during elliptical- and exoskeletal-assisted stepping, an argument for preferentially providing assistance with one type of control strategy or robotic device over the other may not be warranted. During exoskeletal-assisted stepping, hip and knee kinematic trajectories and estimates of consistency (ACC) were very similar to data obtained in participants without neurological injury. However, a previous study has shown that exoskeletal-assisted LT may not be optimal for inducing changes in locomotor performance, particularly compared with therapist-assisted stepping.[21] Furthermore, the magnitude and timing of EMG activity in selected muscles were altered substantially during exoskeletal-assisted stepping as compared to both therapist- and elliptical-assisted stepping. For elliptical-assisted stepping, EMG activity and kinematic consistency were very similar to those for the therapist-assisted stepping condition, although the kinematic (hip) trajectories during elliptical-assisted stepping were significantly different from normal gait kinematics. To mitigate these limitations, specific perturbations could be provided to better optimize stepping patterns with either device. For example, control algorithms for providing variable kinematic trajectories during exoskeletal-assisted stepping could be provided. In addition, providing more BWS and securing the pelvis and trunk more anteriorly during elliptical-assisted training may increase hip extension toward more normal ranges. Such subtle changes may improve patient performance in each device, although the long-term effects with LT are not clear.

Despite these differences in kinematics and muscular activity, metabolic costs were similar between robotic-assisted stepping conditions, and both were significantly less than in the therapist-assisted stepping condition. However, both devices minimize the physical effort on the part of therapists, which may improve delivery to those with substantial weakness. Providing initial assistance with either device may facilitate early practice of LT, and transitioning to therapist-assisted stepping may be warranted with improvements in volitional strength and reduced effort required on the part of the treating therapists. This rationale for providing initial guidance and gradually reducing assistance as warranted is consistent with the guidance hypothesis[46] (also Schmidt and Lee[47]) and may facilitate relearning of independent stepping following neurological injury.

Limitations

Limitations in the present study included a small sample size, lack of ability to evaluate kinetics or ankle kinematics during assisted stepping, and unilateral recordings of EMG activity and kinematics. In addition, we did not quantify the extent of upper-extremity support across each condition, and handrails were not instrumented to estimate upper-extremity forces. If participants did require some handrail support, attempts were made to ensure consistent upper-extremity use across stepping conditions. Furthermore, instructions to work as hard as possible have been used in previous assessments of robotic-assisted stepping performance,[20] although indicators of exertion or effort were not provided as feedback to participants or investigators.

Conclusion

The present article details differences in kinematics, metabolic costs, and muscle activity patterns in participants with iSCI during exoskeletal-, elliptical-, and therapist-assisted stepping. Although the present discussion and previous findings[19–21] suggest that therapist-assisted stepping may elicit better patient performance and improved stepping-related outcomes compared with exoskeletal-assisted stepping, specific limitations of each robotic device limit the ability to provide recommendations for either device over the other. Rather, both devices could be considered a “stepping stone” to eventually transition to therapist-assisted stepping.

The combined findings, therefore, may provide a preliminary strategy for progressing LT and may facilitate selection of devices for use in the clinical setting and their further development. For example, current cost estimates for available exoskeletal robotic orthoses start at more than $200,000, whereas the price of the elliptical devices can be much less (ie, less than $100,000). Differences in cost may be related to the complexity of controlling multiple joint trajectories during stepping versus simpler control of single endpoint kinematics. Importantly, provision of additional feedback, assistance as needed, and flexibility to vary kinematic trajectories and treadmill speeds are possible with some of the current LT devices, and these features may augment patient participation.[48–50] However, such features require additional costs, and their efficacy during LT is uncertain. Future studies might focus on identifying which control strategies can best facilitate stepping performance in patients at varying degrees of recovery following neurological injury.

Dr Hornby, Ms Kinnaird, and Ms Rodriguez provided concept/idea/research design. Dr Hornby, Ms Kinnaird, and Ms Cain provided writing. Dr Hornby, Ms Kinnaird, Ms Holleran, Ms Rafferty, and Ms Rodriguez provided data collection and analysis. Dr Hornby, Ms Kinnaird, and Ms Rafferty provided project management. Dr Hornby provided fund procurement, facilities/equipment, and institutional liaisons. Ms Rodriguez provided study participants. Ms Kinnaird provided clerical support. Ms Kinnaird, Ms Holleran, and Ms Rodriguez provided consultation (including review of manuscript before submission).

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References

1 Behrman A, Harkema S. Locomotor training after human spinal cord injury: a series of case studies. *Phys Ther*. 2000;80:688–700.

2 Behrman A, Lawless-Dixon AR, Davis SB, et al. Locomotor training progression and outcomes after incomplete spinal cord injury. *Phys Ther*. 2005;85:1356–1371.

3 Hesse S, Bertelt C, Jahnke MT, et al. Treadmill training with partial body weight support compared with physiotherapy in nonambulatory hemiparetic patients. *Stroke*. 1995;26:976–981.

4 Macko RF, Ivey FM, Forrester LW, et al. Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: a randomized, controlled trial. *Stroke*. 2005; 36:2206–2211.

5 Moore JL, Roth EJ, Killian C, Hornby TG. Locomotor training improves daily stepping activity and gait efficiency in individuals poststroke who have reached a "plateau" in recovery. *Stroke*. 2010;41:129–135.

6 Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. *Stroke*. 1998;29:1122–1128.

7 Sullivan K, Knowlton BJ, Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. *Arch Phys Med Rehabil*. 2002;83:683–691.

8 Tyson SF, Connell LA, Busse ME, Lennon S. What is Bobath? A survey of UK stroke physiotherapists' perceptions of the content of the Bobath concept to treat postural control and mobility problems after stroke. *Disabil Rehabil*. 2009;31:448–457.

9 Beres-Jones JA, Harkema SJ. The human spinal cord interprets velocity-dependent afferent input during stepping. *Brain*. 2004;127:2232–2246.

10 Harkema S, Hurley SL, Patel UK, et al. Human lumbosacral spinal cord interprets loading during stepping. *J Neurophysiol*. 1997;77:797–811.

11 Maegele M, Muller S, Wernig A, et al. Recruitment of spinal motor pools during voluntary movements versus stepping after human spinal cord injury. *J Neurotrauma*. 2002;19:1217–1229.

12 Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. *J Rehabil Res Dev*. 2000;37:693–700.

13 Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord*. 2001;39:252–255.

14 Lennon S, Ashburn A, Baxter D. Gait outcome following outpatient physiotherapy based on the Bobath concept in people post stroke. *Disabil Rehabil*. 2006;28: 873–881.

15 Hesse S, Sarkodie-Gyan T, Uhlenbrock D. Development of an advanced mechanised gait trainer, controlling movement of the centre of mass, for restoring gait in nonambulant subjects. *Biomed Tech (Berl)*. 1999;44:194–201.

16 Hesse S, Uhlenbrock D, Werner C, Bardeleben A. A mechanized gait trainer for restoring gait in nonambulatory subjects. *Arch Phys Med Rehabil*. 2000;81:1158–1161.

17 Bobath B. *Adult Hemiplegia: Evaluation and Treatment*. 3rd ed. Oxford, United Kingdom: Butterworth-Heinemann; 1990.

18 Lennon S, Baxter D, Ashburn A. Physiotherapy based on the Bobath concept in stroke rehabilitation: a survey within the UK. *Disabil Rehabil*. 2001;23:254–262.

19 Lewek MD, Cruz TH, Moore JL, et al. Allowing intralimb kinematic variability during locomotor training poststroke improves kinematic consistency: a subgroup analysis from a randomized clinical trial. *Phys Ther*. 2009;89:829–839.

20 Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys Ther*. 2006;86:1466–1478.

21 Hornby TG, Campbell DD, Kahn JH, et al. Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke*. 2008;39:1786–1792.

22 Burnfield JM, Shu Y, Buster T, Taylor A. Similarity of joint kinematics and muscle demands between elliptical training and walking: implications for practice. *Phys Ther*. 2010;90:289–305.

23 Horn SD, DeJong G, Smout RJ, et al. Stroke rehabilitation patients, practice, and outcomes: is earlier and more aggressive therapy better? *Arch Phys Med Rehabil*. 2005; 86:S101–S114.

24 Regnaux JP, Saremi K, Marehbian J, et al. An accelerometry-based comparison of 2 robotic assistive devices for treadmill training of gait. *Neurorehabil Neural Repair*. 2008;22:348–354.

25 Israel JF, Hornby TG. Physiological responses of individuals with incomplete spinal cord injury during robotic-assisted treadmill walking. Presented at: Combined Sections Meeting of the American Physical Therapy Association; February 2–6, 2006; San Diego, California.

26 Consortium for Spinal Cord Injury Medicine. *Outcomes Following Traumatic Spinal Cord Injury: Clinical Practice Guidelines for Health-Care Professionals*. Washington, DC: Paralyzed Veterans of America; 1999.

27 El Masry WS, Tsubo M, Katoh S, et al. Validation of the American Spinal Injury Association (ASIA) motor score and the National Acute Spinal Cord Injury Study (NASCIS) motor score. *Spine*. 1996;21:614–619.

28 Dittuno PL, Dittuno JF Jr. Walking Index for Spinal Cord Injury (WISCI II): scale revision. *Spinal Cord*. 2001;39:654–656.

29 Pomeroy VM, Chambers SH, Giakas G, Bland M. Reliability of measurement of tempo-spatial parameters of gait after stroke using GaitMat II. *Clin Rehabil*. 2004;18:222–227.

30 Daly JJ, Roenigk KL, Butler KM, et al. Response of sagittal plane gait kinematics to weight-supported treadmill training and functional neuromuscular stimulation following stroke. *J Rehabil Res Dev*. 2004; 41:807–820.

31 Field-Fote E. Spinal cord stimulation facilitates functional walking in a chronic, incomplete spinal cord injured subject. *Spinal Cord*. 2002;40:428.

32 Fung J, Barbeau H. A dynamic EMG profile index to quantify muscular activation disorder in spastic paretic gait. *Electroencephalogr Clin Neurophysiol*. 1989;73:233–244.

33 Perry J. *Gait Analysis: Normal and Pathological Function*. Thorofare, NJ: Slack Inc; 1992.

34 Hidler J, Wisman W, Neckel N. Kinematic trajectories while walking within the Lokomat robotic gait-orthosis. *Clin Biomech (Bristol, Avon)*. 2008;23:1251–1259.

35 Hornby TG, Campbell DD, Zemon DH, Kahn JH. Clinical and quantitative evaluation of robotic-assisted treadmill walking to retrain ambulation following spinal cord injury. *Top Spinal Cord Inj Rehabil*. 2005;11:1–17.

36 Pohl M, Werner C, Holzgraefe M, et al. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS). *Clin Rehabil*. 2007;21:17–27.

37 Conway BA, Hultborn H, Kiehn O. Proprioceptive input resets central locomotor rhythm in the spinal cat. *Exp Brain Res*. 1987;68:643–656.

38 Pearson K, Collins DF. Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity. *J Neurophysiol*. 1993;70:1009–1017.

39 Hidler JM, Wall AE. Alterations in muscle activation patterns during robotic-assisted walking. *Clin Biomech (Bristol, Avon)*. 2005;20:184–193.

40 Grabowski A, Farley CT, Kram R. Independent metabolic costs of supporting body weight and accelerating body mass during walking. *J Appl Physiol*. 2005;98:579–583.

41 Gottschall J, Kram R. Energy cost and muscular activity required for propulsion during walking. *J Appl Physiol*. 2003;94:1766–1772.

42 Gottschall J, Kram R. Energy cost and muscular activity required for leg swing during walking. *J Appl Physiol*. 2005;99:23–20.

43 Donelan JM, Shipman DW, Kram R, Kuo AD. Mechanical and metabolic requirements for active lateral stabilization in human walking. *J Biomech*. 2004;37:827–835.

44 Macko RF, DeSouza CA, Tretter LD, et al. Treadmill aerobic exercise training reduces the energy expenditure and cardiovascular demands of hemiparetic gait in chronic stroke patients. A preliminary report. *Stroke*. 1997;28:326–330.

45 Macko RF, Smith GV, Dobrovolny CL, et al. Treadmill training improves fitness reserve in chronic stroke patients. *Arch Phys Med Rehabil*. 2001;82:879–884.

46 Winstein CJ, Pohl PS, Lewthwaite R. Effects of physical guidance and knowledge of results on motor learning: support for the guidance hypothesis. *Res Q Exerc Sport*. 1994;65:316–323.

47 Schmidt R, Lee T. *Motor Control and Learning: A Behavioral Emphasis*. 3rd ed. Champaign, IL: Human Kinetics Inc; 1999.

48 Brutsch K, Koenig A, Zimmerli L, et al. Virtual reality for enhancement of robot-assisted gait training in children with central gait disorders. *J Rehabil Med*. 2011;43:493–499.

49 Koenig A, Omlin X, Bergmann J, et al. Controlling patient participation during robot-assisted gait training. *J Neuroeng Rehabil*. 2011;8:14.

50 Koritnik T, Koenig A, Bajd T, Riener R, Munih M. Comparison of visual and haptic feedback during training of lower extremities. *Gait Posture*. 2010;32:540–546.

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Kinematic, Muscular, and Metabolic Responses During Exoskeletal-, Elliptical-, or Therapist-Assisted Stepping in People With Incomplete Spinal Cord Injury

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