Research Report

Metabolic Costs and Muscle Activity Patterns During Robotic- and Therapist-Assisted Treadmill Walking in Individuals With Incomplete Spinal Cord Injury

Background and Purpose. Robotic devices that provide passive guidance and stabilization of the legs and trunk during treadmill stepping may increase the delivery of locomotor training to subjects with neurological injury. Lower-extremity guidance also may reduce voluntary muscle activity as compared with compliant assistance provided by therapists. The purpose of this study was to investigate differences in metabolic costs and lower-limb muscle activity patterns during robotic- and therapist-assisted treadmill walking. Subjects. Twelve ambulatory subjects with motor incomplete spinal cord injury participated. Methods. In 2 separate protocols, metabolic and electromyographic (EMG) data were collected during standing and stepping on a treadmill with therapist and robotic assistance. During robotic-assisted walking, subjects were asked to match the kinematic trajectories of the device and maximize their effort. During therapist-assisted walking, subjects walked on the treadmill with manual assistance provided as necessary. Results. Metabolic costs and swing-phase hip flexor EMG activity were significantly lower when subjects were asked to match the robotic device trajectories than with therapist-assisted walking. These differences were reduced when subjects were asked to maximize their effort during robotic-assisted stepping, although swing-phase plantar-flexor EMG activity was increased. In addition, during standing prior to therapist- or robotic-assisted stepping, metabolic costs were higher without stabilization from the robotic device. Discussion and Conclusion. Differences in metabolic costs and muscle activity patterns between therapist- and robotic-assisted standing and stepping illustrate the importance of minimizing passive guidance and stabilization provided during step training protocols. [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.]

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The efficacy of locomotor training performed using a treadmill with body-weight support (BWS) to improve walking ability in people with motor incomplete spinal cord injury (SCI) has been investigated for more than 20 years.[1,2] Such training is performed by providing partial BWS through a harness-counterweight system over a motorized treadmill while therapists assist the lower limbs and trunk to facilitate independent, upright stepping. Step training performed under appropriate kinetic and kinematic conditions[3,4] enhances lower-limb electromyographic (EMG) activity associated with stepping, which may augment recovery following injury. In particular, lower-limb loading during stance, hip extension in terminal stance, and subsequent unloading and contralateral loading during step transitions provide afferent signals that help regulate the timing and amplitude of appropriate muscle activity during walking.[5–7]

Unfortunately, the practice of locomotor training with a treadmill and BWS may be limited in the clinical setting by the number of therapists and the physical labor often required to provide assistance.[8–10] Various automated (ie, "robotic") devices have been developed to assist therapists in delivering this specific intervention.[10,11] One such device is the Lokomat,[*,12] a computer-controlled, motorized exoskeleton that provides lower-limb and pelvic stabilization in the frontal and sagittal planes and guides the legs through kinematic trajectories approximating human gait. By providing controlled, reciprocal movements, robotic-assisted treadmill stepping may provide many of the afferent cues necessary to enhance locomotion following SCI while reducing the effort required by therapists.[13,14]

A primary limitation of many robotic locomotor devices, including the Lokomat, is the passive guidance provided during treadmill walking. Specifically, the guidance hypothesis[15] suggests that continuous passive assistance applied during task practice reduces subsequent motor performance and retention compared with results achieved with unconstrained practice.[16,17] In neurologically intact subjects, such changes are reflected by reduced voluntary muscle activity during practice and decreased evidence of plastic changes in the central nervous system.[18]

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Despite preliminary evidence indicating that passive, reciprocal lower-limb cycling has been shown to normalize reflex excitability in animal[19] and human[20] motor complete SCI, the effects of passive guidance on the recovery of voluntary upright locomotion (ie, walking) following human incomplete SCI are unknown. Recent studies in subjects without neurological injury suggest that providing assistance to the limbs or trunk during treadmill walking reduces appropriate muscle activity. In particular, providing anteriorly directed forces at the foot to assist swing reduces hip flexor EMG activity.[21] Similarly, providing anteriorly directed forces at the pelvis to aid in propulsion reduces plantar-flexor activity,[22] and lateral stabilization decreases the need for active postural control during walking.[23] Indeed, providing stabilization of the pelvis with a robotic device likely reduces the muscle activity required to maintain postural stability during both standing and stepping. In contrast, therapist assistance at the limbs or pelvis during locomotor training is compliant, or provided only as necessary, requiring patients to voluntarily increase muscle activity to perform standing and stepping tasks. Enhanced neuromuscular activity associated with locomotor training may maximize the activity-dependent plasticity of neural circuits to improve functional ambulation.[7]

To estimate the mechanical work performed by patients during assisted standing or stepping, robotic devices can be instrumented with sensors to quantify subject-generated forces. However, the lack of appropriate instrumentation limits the quantification of lower-limb kinetics during therapist-assisted stepping. In contrast, EMG activity during robotic- or therapist-assisted stepping can be measured to provide an estimate of muscle activity patterns between conditions. Although lower-limb surface EMG recordings can be obtained readily during motor tasks, the quantification of all muscles active during standing or stepping is difficult.[24] In contrast, the use of indirect calorimetry during a locomotor task can provide an estimate of the metabolic cost and a reflection of the net muscle activity.[25] Simultaneous measurements of metabolic costs and EMG patterns during robotic- or therapist-assisted stepping may indicate the contribution of muscle activity patterns to whole-body metabolic costs during assisted stepping.

The purpose of this study was to investigate the differences in metabolic and EMG activity of subjects with motor incomplete SCI during therapist-assisted treadmill walking and during passively guided, robotic-assisted treadmill stepping. In 2 separate protocols, physiological responses were collected prior to and during both robotic- and therapist-assisted walking, with instructions and feedback altered during the robotic-assisted condition. In the first protocol, metabolic and muscle activity patterns were measured during robotic-assisted walking when subjects attempted to match the kinematics of the robotic device (robotic-assisted match protocol [RA-match protocol]). During therapist-assisted walking in this protocol, subjects were asked to walk on the treadmill with compliant, manual assistance at the lower limbs or trunk. In the second protocol physiological responses were obtained when subjects were provided with augmented visual feedback of locomotor kinetics and were asked to maximize their effort during robotic-assisted stepping (robotic-assisted maximal effort protocol [RA-max protocol]). Responses were again compared with those obtained during therapist-assisted stepping.

We anticipated differences in metabolic costs and muscle activity patterns between robotic- and therapist-assisted walking conditions, which were dependent on the instructions and feedback provided. At identical speed and BWS, we hypothesized that compliant assistance provided during therapist-assisted walking would generate higher metabolic costs as compared with robotic-assisted conditions, particularly during the RA-match protocol. Such differences would be reflected by increased, phase-specific EMG activity of the hip flexors during swing and plantar flexors during midstance to terminal stance. In addition, we expected an increased metabolic cost of standing on the treadmill without pelvic or limb restraint prior to therapist-assisted standing. Differences in physiological responses observed during standing and treadmill walking with robotic device or therapist assistance in the 2 separate protocols may provide information on how passive guidance and specific instructions or feedback may alter the muscle activity of patients with motor incomplete SCI. Such knowledge may be important for therapists using robotic devices to maximize voluntary locomotor performance during assisted stepping to augment the recovery of functional walking.

Method

Subjects

Subjects with motor incomplete SCI were recruited from the Rehabilitation Institute of Chicago. Subjects ranged from 15 to 59 years of age and had a classification of C or D on the American Spinal Injury Association (ASIA) impairment scale.[26] Inclusion criteria were lower-extremity range of motion consistent with normal gait, absence of unhealed decubiti, no history of osteoporosis or recurrent lower-extremity fractures, no history of lower-extremity peripheral nerve injury, and lack of metabolic or cardiopulmonary instability.

After written informed consent was obtained, medical records were reviewed and an examination was performed. Clinical assessments included an ASIA examina-

Table 1.
Subject Characteristics[a]

Subject No.	Age (y)	Level of Injury	ASIA Impairment Classification	Duration of SCI (mo)	ASIA LEMS	Gait Speed (m/s)	WISCI II	Type of Ambulation
1	19	T10	C	14	39	0.16	13	Household
2	59	T9–T10	D	18	48	0.51	9	Community
3	46	C4–C6	C	34	34	0.59	13	Household
4	50	C5–C6	C	181	28	0.36	13	Household
5	27	C7	D	11	37	0.45	19	Community
6	42	T2	D	21	37	1.06	19	Community
7	17	C6	D	15	30	0.41	13	Community
8	38	C5	C	58	14	0.09	13	Household
9	25	C4–C5	C	15	28	0.10	9	Household
10	15	C5–C6	D	24	46	0.70	16	Community
11	37	C3–C5	D	5	48	0.17	15	Household
12	47	C4	D	226	41	0.40	15	Community

[a] ASIA=American Spinal Injury Association, SCI=spinal cord injury, LEMS=Lower-Extremity Motor Score, WISCI II=Walking Index for Spinal Cord Injury II.

tion of lower-extremity motor scores, in which ordinal numbers (0–5) were assigned to 5 muscle groups bilaterally to obtain the Lower Extremity Motor Score (total=50).[27,28] Assessment by ASIA examination in subjects with incomplete SCI has demonstrated concurrent validity with other manual muscle assessments[29] but only moderate interrater reliability (kappa statistics=.48–.89).[30] Preferred over-ground gait speed was determined with the GaitMat II,[†] a walking platform with embedded pressure switches that can detect spatial-temporal gait parameters. The concurrent validity of the data collected with this device versus handheld stopwatch measures in subjects with SCI[31] and community-dwelling older adults[32] has been demonstrated. High interrater reliability also has been established.[31,33] The Walking Index for Spinal Cord Injury II (WISCI II)[34] was used to evaluate the use of braces, assistive devices, and physical assistance. Although the WISCI II is modified slightly from the WISCI, interrater agreement has been found to be 100% for the initial WISCI scale,[35] and concurrent validity of the WISCI with other mobility scales in human SCI has been demonstrated.[35,36]

Table 1 shows the clinical characteristics of the 12 subjects who participated in the experiments; subjects 1 through 8 participated in both protocols, subjects 9 and 10 participated in the RA-match protocol only, and subjects 11 and 12 participated in the RA-max protocol only. Subjects 11 and 12 were matched as closely as possible to subjects 9 and 10 according to lesion level and walking ability. All subjects walked over ground without physical assistance but with bracing and devices as needed and had been exposed to at least 5 sessions of therapist- and robotic-assisted walking.

Experimental Design

The RA-match and RA-max protocols were performed on different days at least 7 days apart; metabolic and muscle activity data were collected during therapist- and robotic-assisted treadmill walking each day. During therapist-assisted walking, metabolic and muscle activity data were collected when subjects were simply asked to walk on the treadmill independently, and manual assistance was provided as needed (described below). During robotic-assisted training, both the set of instructions and the extent of biofeedback provided to the users varied between protocols. In the RA-match protocol, metabolic and muscle activity data were collected during robotic-assisted walking with instructions to "walk with the robot" and match the trajectories of the device. In the RA-max protocol, physiological measures were collected when subjects were asked to generate maximum effort during robotic-assisted walking.

Experimental Procedures and Instruments

The details of the experimental setup for treadmill walking with therapist and robotic device assistance were described previously.[13,14] Subjects were secured over a motorized treadmill[‡] with a harness-counterweight system. The amount of BWS was set at 30% to 40% for all subjects[37] and kept constant between walking conditions.

During robotic-assisted walking, the exoskeletal orthosis was aligned and secured to subjects with thigh and shank cuffs and pelvis straps attached to the harness. Spring-loaded cloth straps were attached to the subject's forefoot to ensure toe clearance during swing. The robotic device was attached to the treadmill support frame with a spring-loaded, 4-bar linkage such that the net vertical

[†] EQ Inc, PO Box 16, Chalfont, PA 18914-0016.

[‡] Woodway GmbH, Steinackerstrasse 20, D79576 Weil am Rhein, Germany.

force of the device was considered to be negligible. Linear actuators at bilateral hip and knee joints were programmed by 2 computers and a current controller to generate a symmetrical gait pattern timed to the treadmill speed. Step length was adjusted by a program* designed by the manufacturer to alter hip range of motion during stepping by estimating step length from shank length. Step length was further adjusted to approximate normal kinematics as described previously.[8]

During therapist-assisted walking, manual assistance was provided as necessary to the lower extremities by up to 2 therapists positioned at each leg. All lower-extremity orthoses were removed prior to treadmill standing and walking. During stepping, therapists assisted knee flexion during swing and extension during stance by specific hand placement on the posterolateral or anterolateral aspect of the knee as required. Toe clearance was facilitated by grasping the foot dorsum and assisting during swing. When necessary, trunk support also was provided by cloth straps attached anteriorly and laterally to the handrails of the treadmill and around the supporting harness (used in 7 of 10 subjects in both protocols). The cloth straps therefore provided frontal and sagittal (anterior) support on the treadmill to assist with postural stabilization and forward propulsion if necessary. If assistance provided by therapists or the cloth straps was not necessary to approximate normal walking kinematics, subjects walked without manual facilitation at either limb or at the pelvis. However, if subjects demonstrated compensatory strategies during walking (eg, hip circumduction during swing), therapists attempted to provide manual guidance to facilitate normal limb trajectories (eg, knee flexion assistance with reduced frontal-plane hip movement). During both training paradigms, upper-extremity weight bearing was discouraged, although subjects were asked to rest their arms on the bilateral handrails to minimize arm movements, which could alter metabolic costs (however, see Behrman and Harkema[8]).

The rates of oxygen (O_2) consumption [$\dot{V}O_2$ (milliliters per kilogram per minute)] and carbon dioxide (CO_2) production ($\dot{V}CO_2$) were collected by use of a mobile metabolic cart (Vmax29 series cardiopulmonary testing instrument[§]) for the RA-match protocol or a portable metabolic unit ($K4b^2$ series cardiopulmonary testing instrument[‖]) for the RA-max protocol. Both instruments were calibrated similarly prior to testing sessions using room air and a reference gas mixture with a known composition (16% O_2 and 5% CO_2).

Surface silver-silver chloride electrodes (SureTrace[#]) were applied to the muscles of a single limb following standard skin preparation. Muscles tested included tibialis anterior (TA), soleus (SOL), medial gastrocnemius (MG), vastus lateralis (VL), rectus femoris (RF), and medial hamstring (MH) muscles. Recording of the iliopsoas, a primary hip flexor, with surface electrodes was not considered feasible, although the RF muscle is considered a valid indicator of hip flexor activity.[21] Footswitches** also were secured under the heel of the footwear of the tested limb.

Experimental Protocol

Metabolic measurements were obtained during sitting for 5 minutes prior to walking trials. Prior to either therapist- or robotic-assisted walking, metabolic costs were collected during standing with BWS for 2 minutes. When required to walk with robotic assistance, subjects were positioned in the device in standing prior to data collection. When required to walk with therapist assistance, subjects stood independently without therapists supporting the lower extremities and without upper-extremity weight bearing.

After standing measurements were collected, subjects walked continuously for 10 minutes on the treadmill (robotic- or therapist-assisted) at a speed of 3.0 km/h (ie, in the range of normal walking speed recommended for locomotor training[8]). During robotic-assisted walking in the first protocol (RA-match protocol), subjects were asked to "walk with the robot" and match the trajectories of the device. No visual feedback was provided during training, and subjects were unaware of their performance. During therapist-assisted walking, subjects were asked to attempt to walk independently as therapists provided verbal cues and manual assistance only as necessary. In each protocol, 6 subjects required bilateral assistance during therapist-assisted training, and 4 subjects required unilateral assistance. Following 10 minutes of walking, subjects were brought to the sitting position and remained sitting for 10 minutes while metabolic responses were collected continuously.

Following a return to baseline (sitting) $\dot{V}O_2$ levels, subjects were asked to repeat the protocol sequence, but with the walking condition changed. Testing order was pseudorandom, with half of the subjects walking with robotic assistance first. The duration between conditions was approximately 15 to 25 minutes.

In the second protocol (RA-max protocol), sitting and standing measurements were collected as described above for the RA-match protocol. Therapist-assisted

§ SensorMedics, 22745 Savi Ranch Pkwy, Yorba Linda, CA 92887-4645.
‖ COSMED USA Inc, 2758 N Paulina, Chicago, IL 60614.
CONMED Corp, 310 Broad St, Utica, NY 13501.
** Noraxon USA Inc, 13430 N Scottsdale Rd, Suite 104, Scottsdale, AZ 85254.

walking was performed as described previously, but instructions during robotic-assisted walking were to maximize voluntary effort, with visual feedback of performance provided. Specifically, forces detected along the spindle axis of bilateral hip and knee joints by single-axis load cells were used as an approximation of the torques generated by the subject and were displayed on a computer monitor.[38] A custom-made computer program identified "baseline" as the effort required to move the exoskeletal legs through the predetermined kinematic trajectories without external perturbations (ie, subjects not placed in the device) during both stance and swing phases. The feedback indicated a decrease from baseline if the user was not generating sufficient hip or knee torque to match the robotic-generated trajectories. All subjects were fitted in the device and instructed in the use of the biofeedback prior to testing. During either the RA-match or the RA-max protocol, forces were not recorded, as there was no ability to accurately record forces during therapist-assisted walking.

Data Collection and Analysis

Measurements of $\dot{V}O_2$ and $\dot{V}CO_2$ were collected on a breath-by-breath basis and averaged over 20-second intervals.[39] Steady-state $\dot{V}O_2$ was determined when the rate of increasing $\dot{V}O_2$ was $\leq$1 mL/kg/min for 3 consecutive 20-second epochs and was observed after 3 minutes in all subjects. The metabolic cost of walking (or power [P_{met}], in watts [W]) was calculated using standard equations,[40] where P_{met}=16.58 W·s/mL of O_2 ($\dot{V}O_2$)+4.51 W·s/mL of CO_2 ($\dot{V}CO_2$). The P_{met} of walking was determined by subtracting values calculated during standing from values calculated during walking values, and normalizing to body mass (W/kg).[41] Trials in which respiratory quotient (ie, RQ=$\dot{V}CO_2/\dot{V}O_2$) were greater than 1.0 were excluded from this calculation (1 subject during the RA-max protocol).

The EMG signals were amplified (×1,000) and filtered (10–500 Hz) with a MyoSystem 1400.** The EMG and footswitch data were sampled at 1,000 Hz for 10 to 20 seconds during steady state (minutes 4–6) with a custom-made MATLAB†† program and were stored on a personal computer. The EMG data were used only from subjects for whom data were collected for at least 10 strides during each walking condition (>7 subjects for each muscle, consistent with previously published data[9]). Gait phases (bins) were identified previously[9] during robotic-assisted and unassisted treadmill walking in subjects without neurological injury and corresponded to the following percentages of the gait cycle: initial loading (0%–12%, phase 1), mid-stance (12%–30%, phase 2), terminal stance (30%–50%, phase 3), preswing (50%–62%, phase 4), initial swing (62%–75%, phase 5), midswing (75%–87%, phase 6), and terminal swing (87%–100%, phase 7). The root-mean-square (RMS) of the rectified EMG data during the gait phases was calculated and normalized to the maximum RMS during walking,[42] which can exceed values achieved during voluntary tasks performed in the sitting position in subjects with SCI.[4,43]

Statistical analyses focused on the differences in metabolic costs and muscle activity patterns between robotic- and therapist-assisted walking in each protocol, with the significance set at $P<.05$. A 2-way analysis of variance (ANOVA) was used to assess the effects of order and condition on baseline metabolic standing and steady-state walking (minutes 4–6) measures. Unpaired *t* tests were performed on metabolic costs during therapist-assisted walking in each protocol between days of testing or for 2 different subjects. Unpaired comparisons also were performed on data collected during robotic-assisted walking in each protocol.

A 2-way repeated-measures ANOVA was performed between walking condition and phase of gait (repeated for 7 gait phases) on RMS EMG data averaged over minutes 4 to 6 for all muscles. If differences were significant, Tukey-Kramer *post hoc* tests were performed to identify differences in EMG data between walking conditions during specific gait phases. Paired *t* tests were performed on stepping cadence between conditions.

Differences in metabolic costs (ΔP_{met}) and muscle activity (ΔEMG) between walking conditions were calculated to identify relationships between variables. Specifically, ΔP_{met} values were determined by subtracting P_{met} during robotic-assisted walking from P_{met} during therapist-assisted walking to account for potential intra- or intersubject variability in metabolic costs.[44] Similarly, ΔEMG were calculated as therapist-assisted EMG activity minus robotic-assisted EMG activity. This procedure normalized the metabolic and EMG responses between trials to provide a relative difference between conditions. Correlation and regression analyses were performed on ΔP_{met} and ΔEMG to identify whether observed significant differences in EMG activity were associated with metabolic costs of walking.

Results

Metabolic Parameters

The metabolic responses varied substantially both between therapist- and robotic-assisted conditions and between protocols during standing and walking (Tab. 2). In the RA-match protocol, $\dot{V}O_2$ during standing was significantly higher prior to therapist- and robotic-assisted conditions. During steady-state walking, a large increase in $\dot{V}O_2$ from standing was observed in both

†† The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

Table 2.
Changes in Metabolic Measures Within and Between Protocols[a]

	RA-match Protocol		RA-max Protocol	
	Robotic-Assisted	Therapist-Assisted	Robotic-Assisted	Therapist-Assisted
Sitting $\dot{V}O_2$ (mL/kg/min)	3.6±1.0		3.4±0.6	
Standing $\dot{V}O_2$ (mL/kg/min)	3.4±0.7	5.2±2.2[b]	4.1±1.1	5.4±1.2[b]
Steady-state $\dot{V}O_2$ (mL/kg/min)	9.0±2.4[c]	14±3.9[d]	14±3.2	15±2.0
Metabolic cost (power, W/kg)	1.9±0.8[c]	3.1±1.4[b]	3.3±1.3	3.5±0.8
$\dot{V}CO_2/\dot{V}O_2$ (respiratory quotient, no units)	0.84±0.09	0.89±0.07	0.86±0.08	0.87±0.09

[a] Baseline (sitting and standing) and walking metabolic responses during both protocols are provided. Values are reported as means ± standard deviations. $\dot{V}O_2$=rate of oxygen consumption. $\dot{V}CO_2$=rate of carbon dioxide production.
[b] Significant difference between robotic- and therapist-assisted walking ($P<.05$).
[c] $P<.05$ for unpaired comparisons between the robotic-assisted conditions in the 2 protocols; there was no difference in metabolic costs between the therapist-assisted walking conditions.
[d] Significant difference between robotic- and therapist-assisted walking ($P<.01$).

groups, although differences between conditions were observed. Specifically, in the RA-match protocol, steady-state $\dot{V}O_2$ and P_{met} were 34%±17% (mean±SD; $P<.01$) and 31%±32% ($P<.05$) higher, respectively, for therapist- and robotic-assisted conditions. In the RA-max protocol, differences in $\dot{V}O_2$ during standing prior to therapist- and robotic-assisted conditions were again observed, although differences during walking were minimal (Tab. 2). In both experiments, there was no effect of testing order on metabolic measures and no differences in RQ values. Metabolic costs during therapist-assisted walking conditions between protocols were similar ($P>.30$), whereas differences in metabolic costs between robotic-assisted walking in the RA-match protocol and robotic-assisted walking in the RA-max protocol were significant.

EMG Measurements

Muscle activity patterns during identified phases of the gait cycle[9] were analyzed in both protocols. A single-subject example of EMG activity during therapist- and robotic-assisted walking in the RA-match protocol is shown in Figure 1. For comparison, shaded horizontal bars indicate the phase of the gait cycle during which EMG activity is observed in people without gait dysfunction during over-ground walking[24] and treadmill walking.[9] For the TA, SOL, and MG muscles (Figs. 1A–1C), elevated EMG activity was evident primarily during stance. Such activity is

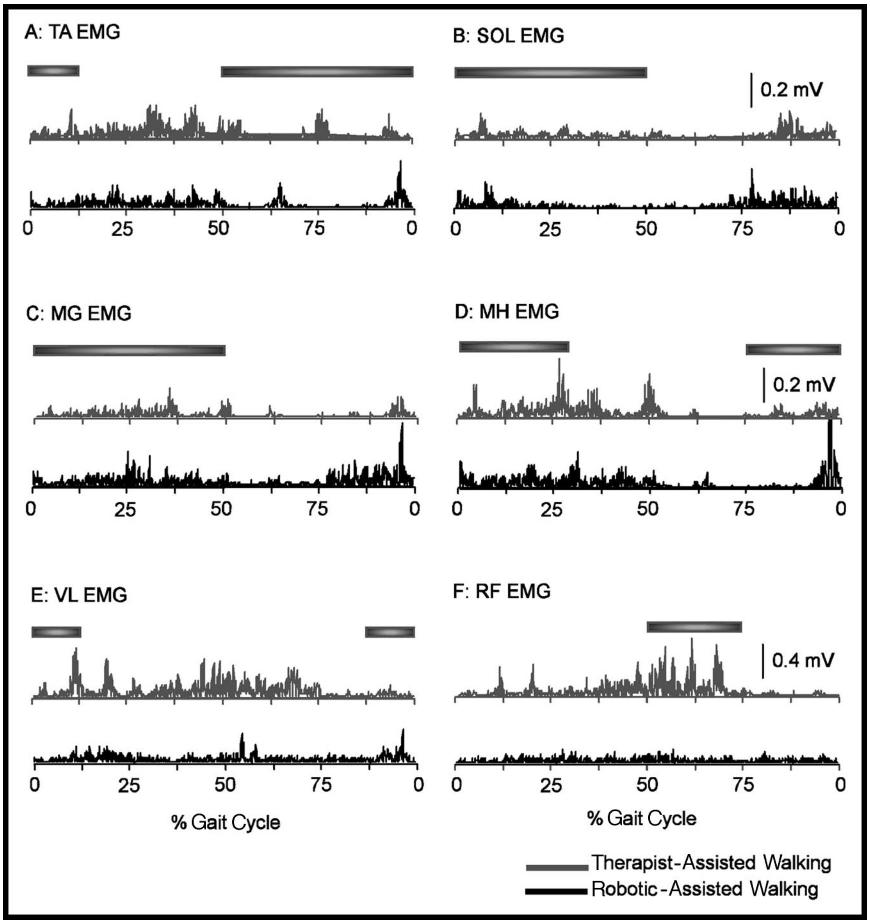

Figure 1.
Rectified electromyographic (EMG) data from 1 subject during a single gait cycle for 6 muscles: (A) tibialis anterior (TA), (B) soleus (SOL), (C) medial gastrocnemius (MG), (D) medial hamstring (MH), (E) vastus lateralis (VL), and (F) rectus femoris (RF). Gray traces represent EMG data recorded during therapist-assisted walking, and black traces represent robotic-assisted walking activity. Therapist-assisted walking was shown to elicit greater RF muscle EMG activity during preswing (see Fig. 3F). Shaded horizontal bars indicate where normal EMG activity is present in neurologically intact people during over-ground walking.

appropriate for extensor muscles, while the TA should remain silent during mid-stance and terminal stance. During swing, all muscles were relatively quiescent until terminal swing, during which MG and SOL EMG patterns were more prominent during robotic-assisted walking. For proximal muscles (Figs. 1D–1F), MH and VL EMG activity patterns were generally similar between conditions and approximated EMG data observed in subjects who were healthy during over-ground walking, although a longer duration of VL activity was observed during stance. For the RF, however, EMG activity was observed in this example only during preswing in the therapist-assisted walking condition, with very little EMG activity in the robotic-assisted condition.

Normalized EMG patterns averaged across subjects were consistent with the individual data shown. Figure 2 demonstrates the averaged, normalized EMG during both robotic- and therapist-assisted walking in the RA-match protocol for each phase of the gait cycle.[24] The 2-way repeated-measures ANOVA revealed significant main effects for the phase of the gait cycle for nearly all muscles ($P<.01$). One notable exception was the TA (Fig. 2A), which demonstrated little modulation between phases, consistent with previous reports for people with SCI during assisted walking.[43] Significant main effects were not observed for walking condition for all muscles, although interaction effects were noted for RF (Fig. 2F) and MG (Fig. 2C) ($P<.05$). *Post hoc* tests demonstrated significant differences only for RF, however. An increase in RF EMG activity during the preswing phase (bin 4 in Fig. 2) was observed during therapist-assisted walking, with a smaller difference noted during initial loading (bin 1 in Fig. 2).

In the RA-max protocol, EMG activity for all muscles except TA varied significantly throughout the gait cycle during both therapist- and robotic-assisted treadmill walking (Fig. 3). Significant main effects between conditions were not observed in any muscle, although

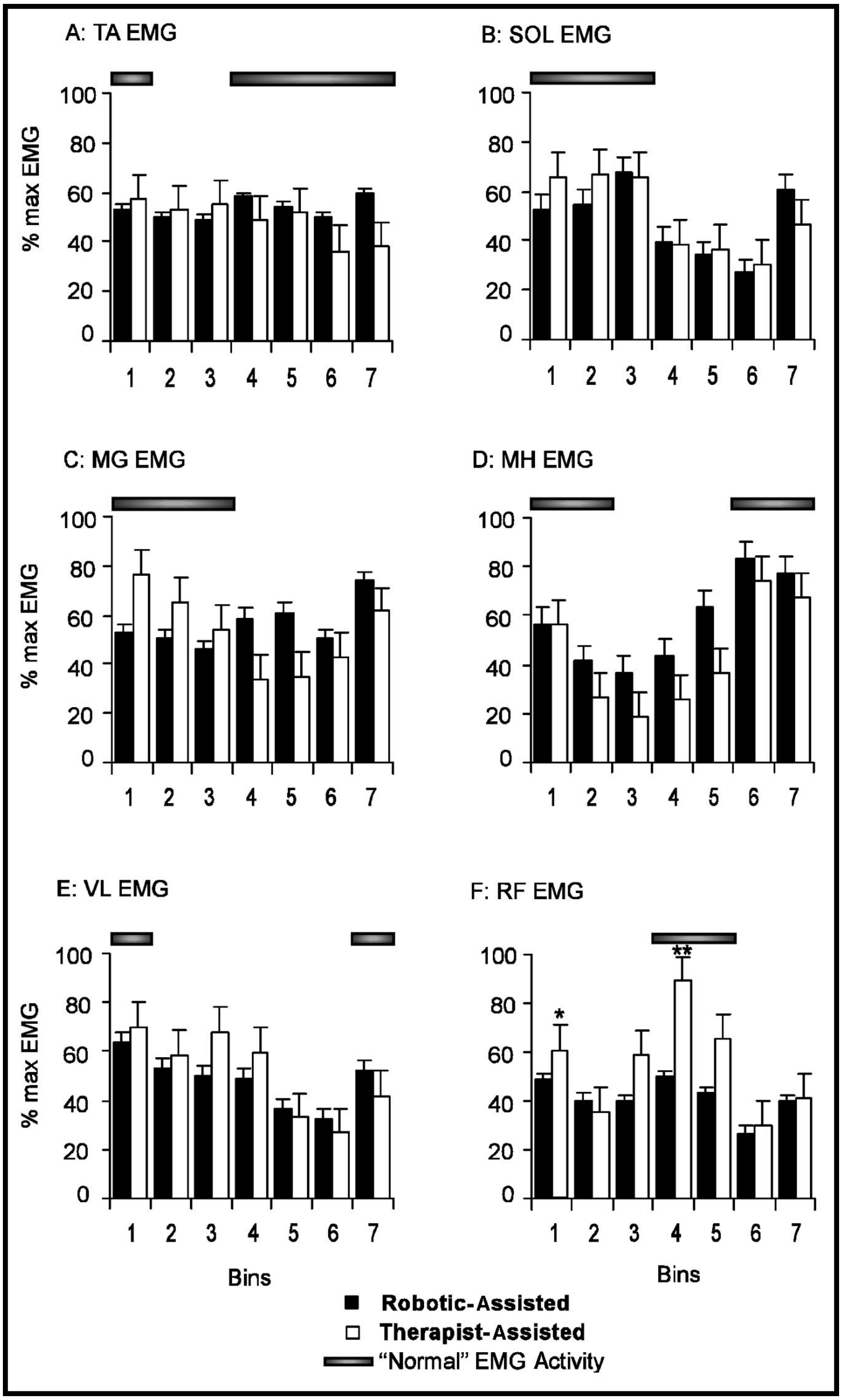

Figure 2.
Normalized root-mean-square electromyographic (EMG) data for each phase of the gait cycle during steady state in both therapist-assisted and robotic-assisted conditions of the robotic-assisted match protocol. *=$P<.05$. **=$P<01$. Shaded horizontal bars indicate where normal EMG activity is present in neurologically intact people during over-ground walking. The rectus femoris muscle was the only muscle to demonstrate statistically significant differences between the walking conditions, with greater activity at preswing and initial loading during therapist-assisted walking. Muscles were as follows: (A) tibialis anterior (TA), (B) soleus (SOL), (C) medial gastrocnemius (MG), (D) medial hamstring (MH), (E) vastus lateralis (VL), and (F) rectus femoris (RF). max=maximum. Error bars indicate standard deviations.

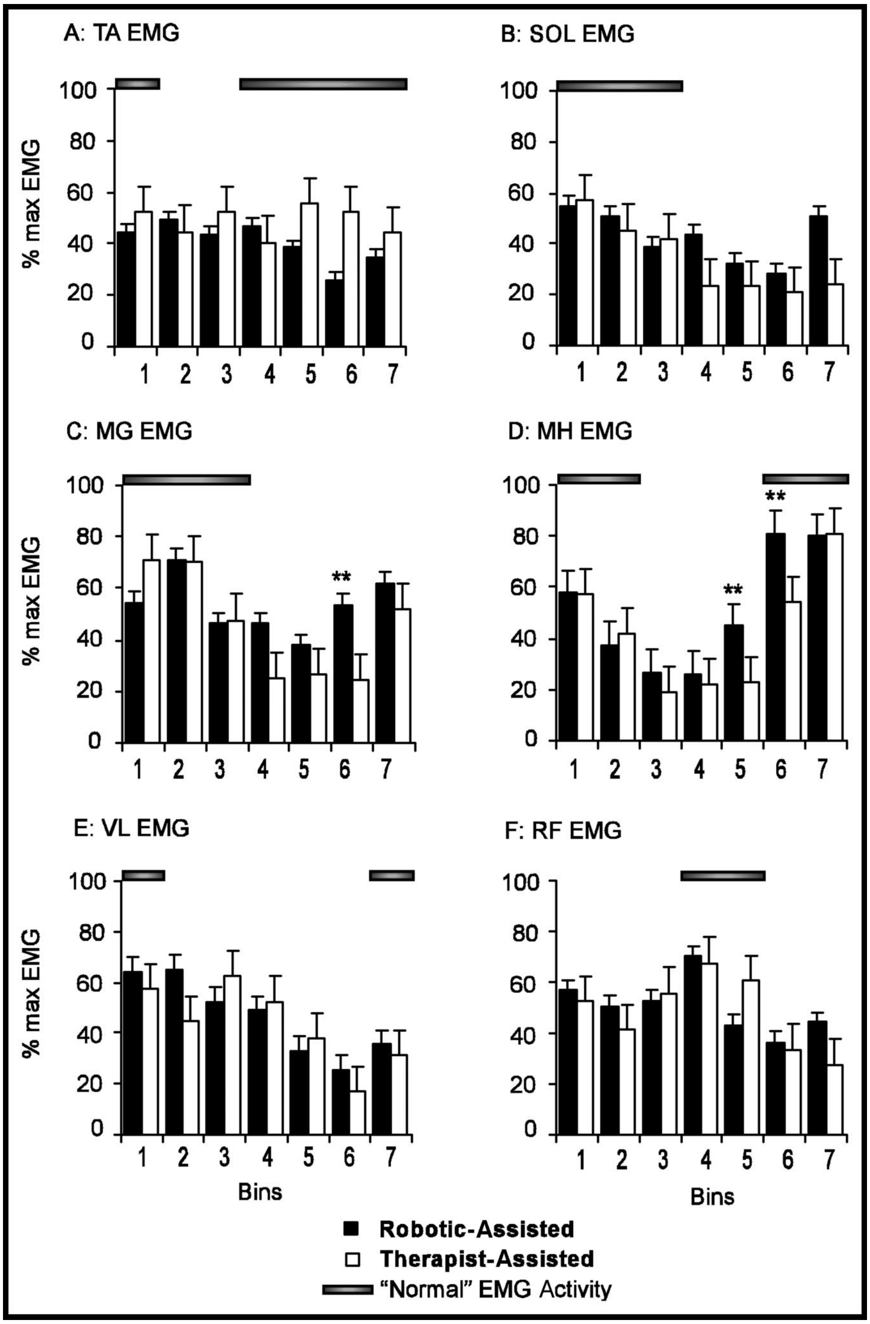

Figure 3.
Normalized root-mean-square electromyographic (EMG) data for each phase of the gait cycle during steady state in both therapist-assisted and robotic-assisted conditions of the robotic-assisted maximum protocol. **=$P<.01$. Shaded horizontal bars indicate where normal EMG activity is present during over-ground walking in people who are neurologically intact. No difference in rectus femoris muscle activity was observed, whereas differences in medial hamstring and medial gastrocnemius muscle activities were evident during the swing phase. Muscles were as follows: (A) tibialis anterior (TA), (B) soleus (SOL), (C) medial gastrocnemius (MG), (D) medial hamstring (MH), (E) vastus lateralis (VL), and (F) rectus femoris (RF). max=maximum. Error bars indicate standard deviations.

interaction effects were noted for the MG and MH muscles but not the hip flexors (ie, RF). Specifically, knee flexor (MH) activity was elevated during the initial and midswing phases in the robotic-assisted walking condition, while MG EMG activity was increased during midswing to terminal swing. Notably, elevated MG muscle activity during swing is not observed in subjects who were neurologically intact during normal over-ground walking,[24] treadmill walking, or robotic-assisted walking.[9]

Relationship Between Metabolic Costs and Muscle Activity

Differences in RF, MG, and MH activity patterns between walking conditions and protocols prior to or during swing appeared to modulate with differences in metabolic costs. To determine the association between muscle and metabolic responses, ΔP_{met} between walking conditions were calculated for both protocols (ie, RA-match and RA-max protocols) and compared with ΔEMG. Specifically, ΔEMG was calculated only for RF, MH, and MG muscles and only during phases of gait in which significant differences were observed in either protocol. Figure 4 demonstrates a significant relationship between preswing RF ΔEMG and ΔP_{met} ($P<.01$), indicating a substantial contribution of hip flexor activity to the metabolic costs of walking. There were no other significant relationships observed for other muscles ($r^2<.18$, $P>.10$).

Discussion and Conclusions

In the present investigation, differences in the metabolic costs of treadmill walking in subjects with motor incomplete SCI were demonstrated between robotic- and therapist-assisted conditions and were dependent on the instructions and feedback provided to the subjects. Specifically, as compared with therapist-assisted stepping, metabolic costs were significantly lower during robotic-assisted stepping when subjects were asked to match the trajectory of the device. Differences in metabolic costs were partially accounted for by the reduced hip flexor EMG activity demonstrated during robotic-assisted walking. Reduced metabolic activity observed during quiescent standing in the robotic-assisted condition also may have contributed to the differences observed during walking. When subjects were asked to maximize their effort during robotic-

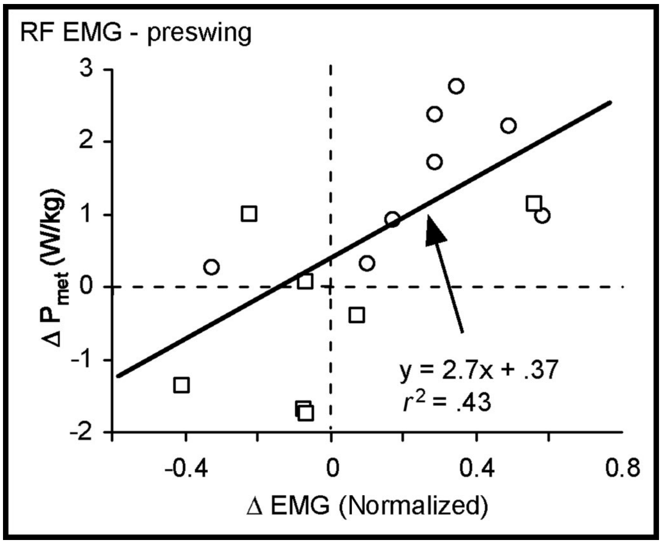

Figure 4.
Correlation analyses and regression equations for differences in metabolic costs (ΔP_{met}) and muscle activity (ΔEMG) for the rectus femoris (RF) muscle during preswing in both protocols combined. Open circles indicate data collected during the robotic-assisted match protocol, and open squares indicate data collected during the robotic-assisted maximum protocol. There was a significant correlation ($P<.01$) between ΔP_{met} and ΔEMG for the RF muscle, although no difference was demonstrated for other muscles.

assisted stepping, however, differences in metabolic costs and hip flexor EMG activity were smaller, although plantar-flexor EMG activity was elevated during periods in which the muscles are typically quiescent.

Simultaneous collection of metabolic and EMG measurements during robotic- and therapist-assisted treadmill walking in people with neurological injury has not been performed previously. A recent study[45] demonstrated significant increases in cardiac and metabolic responses during a single bout of robotic-assisted treadmill walking in a subject with motor complete SCI,[45] although no comparison with therapist-assisted walking was made. In another study,[46] lower-limb EMG recordings collected from 2 subjects with SCI (1 complete and 1 incomplete) during robotic- and therapist-assisted walking indicated to the authors that the muscle activity patterns between conditions were similar. In the present study, however, simultaneous collection of data for metabolic and muscle activity provided an indication of the potentially large differences in physiological costs of robotic- and therapist-assisted treadmill walking when specific instructions and feedback are provided.

Metabolic Costs and Muscle Activity During Therapist- and Robotic-Assisted Walking

Differences in muscle activity and metabolic costs of robotic- and therapist-assisted treadmill walking may be partially explained by various biomechanical constraints provided during the 2 walking conditions. For example, alterations in cadence/step length and velocity[41,47] can alter the metabolic costs of walking, although both variables were similar between conditions. Lower-extremity loading also contributes substantially to extensor EMG activity and metabolic costs of walking,[48] although the amounts of BWS were equivalent between conditions and there were no differences in primary extensor (VL, SOL, and MG) activation patterns. Although a small increase in RF muscle EMG activity during therapist-assisted walking at initial loading was observed in the RA-match protocol, the contribution of this activity to metabolic costs likely was minimal because of the weak correlation between ΔP_{met} and ΔEMG for the RF muscle during stance. Furthermore, although subjects were asked to rest their arms on the bilateral handrails during walking, we did not measure upper-extremity muscle activity or weight bearing, which may have contributed to the differences observed between tasks. Subjects, however, were discouraged from upper-extremity weight bearing during walking.

We believe that 2 primary factors can account for the differences in metabolic costs between walking conditions. The first is the passive guidance provided by the device, particularly during the swing phase. In subjects without neurological injury, providing anteriorly directed forces to the foot during swing decreased the magnitudes of RF (60%) and iliopsoas (27%) EMG activity. Such differences were accompanied by accompanied by reduced metabolic costs during walking.[21] Accordingly, in the present study, preswing RF muscle EMG activity and metabolic costs were reduced during robotic- and therapist-assisted walking in the RA-match protocol, although differences in both variables were minimized by asking subjects to increase their voluntary effort during robotic-assisted walking (ie, during the RA-max protocol). The significant association between ΔP_{met} and ΔEMG for the RF muscle during preswing further indicated that hip flexor activity played a role in the observed differences.

The second primary factor thought to account for the differences in metabolic costs during treadmill walking was the lateral and sagittal stability provided by the robotic device.[22,23,49] Metabolic costs during robotic-assisted standing as compared with the costs generated during unassisted standing were significantly different in both protocols prior to treadmill walking (Tab. 2). During quiescent standing on the stationary treadmill, the device allows for sagittal movement at the hips and knees, while pelvic and trunk motion are restricted. Pelvic and trunk stabilization during standing and walking could be considered a form of passive guidance in which the muscular work required to generate active sagittal- and frontal-plane stabilization is minimized. Indeed, stabilization of the pelvis has been shown to substantially reduce metabolic costs during locomotor tasks[23,50] and may have contributed to the differences observed in the present study.

One additional caveat regarding the pelvic stabilization provided by the robotic device is the provision of posterior support, which can assist in forward propulsion during treadmill walking. In particular, the muscular work associated with forward propulsion is thought to be a primary determinant of the metabolic costs of walking in subjects without neurological injury. Specifically, providing anterior forces at the pelvis reduces the metabolic costs of treadmill walking and reduces stance-phase MG activity associated with propulsion.[22] We therefore expected increased MG activity during mid-stance to terminal stance during therapist-assisted walking, although this expectation was not supported by the data in either protocol. A likely explanation to account for the lack of differences may be the cloth straps attached to the harness and the treadmill handrails used to aid propulsion during therapist-assisted walking. In more than half of the subjects tested in either protocol, providing anteriorly directed support likely reduced a subject's muscle activity necessary to generate propulsive forces, although it facilitated the ability to maintain the desired walking speed. It is unlikely, therefore, that propulsive assistance played a substantial role in the observed differences in metabolic costs, although such assistance provided in either condition likely contributed to the net metabolic costs.

"Abnormal" Muscle Activity During Robotic-Assisted Walking

In addition to the RF muscle, increased RMS values of MH and MG EMG were observed during robotic-assisted walking, but only in the RA-max protocol during the swing phase of walking. Muscle activity from either muscle is typically not observed during these specific gait phases during over-ground walking in people without neurological injury. Specifically, MH activity was greater during initial swing and midswing, when hamstring EMG activity typically is minimal.[24] However, subjects were encouraged to exert their maximum effort during stepping in the RA-max protocol and likely increased knee flexor activity accordingly. A previous study that evaluated the effects of robotic assistance on muscle activation patterns in subjects without neurological injury[9] also demonstrated greater hamstring EMG activity during swing as compared with unassisted treadmill walking. This finding was accounted for by subjects "pulling" upward on the robotic device (ie, increasing knee flexion), which may have occurred in the present study as well.

Medial gastrocnemius activity also was greater during the swing phase of robotic-assisted walking in the RA-max protocol, approximating the magnitude of EMG activity obtained during stance. Although the MG can function as a knee flexor, triceps surae activity is minimal during swing.[24] Furthermore, large increases in MG activity are not observed in subjects without neurological injury during robotic-assisted walking.[9] We believe that "inappropriate" MG activity in the subjects tested in the present study may be caused by hyperexcitable responses to afferent stimuli (ie, hyperreflexia). Specifically, the use of metatarsal straps to ensure toe clearance may have provided abnormal input to the plantar-flexor motor pools during the swing phase. Elevated MG muscle activity during swing may be attributable to increased stretch[51] generated with a fixed ankle position during imposed knee extension or mechanical loading produced by the elastic straps at the sole of the foot.[52,53] The combination of altered afferent input during robotic-assisted walking and hyperexcitable reflex activity likely resulted in the augmented MG muscle activity during the swing phase.

Clinical Significance and Future Directions

In the absence of the results of a randomized controlled trial comparing the relative effectiveness of locomotor training with robotic- and therapist-assisted treadmill walking in ambulatory subjects with incomplete SCI, the data presented here may provide some indication of how robotic-assisted training could be used in the clinical setting. Specifically, if enhanced, appropriate neuromuscular activity during practice of voluntary stepping is important for maximizing activity-dependent plasticity of spinal and supraspinal locomotor circuitry following SCI, then the use of robotic-assisted training should be minimized. Although many of the afferent cues associated with upright stepping may be provided during robotic-assisted stepping, specific limitations of the robotic locomotor device used in the present study, including passive guidance, pelvic restraint, and provision of extraneous afferent inputs (eg, metatarsal straps), limited the generation of appropriate muscle activity associated with independent walking. Importantly, at least the first 2 of these items may reduce the voluntary participation of subjects during robotic-assisted training, which is thought to be critical for maximizing motor learning. Although previous studies[13,14,54,55] documented improvements in over-ground walking in subjects with incomplete SCI following robotic-assisted locomotor training, it is unclear whether the walking recovery was maximized.

Despite the limitations addressed above and previously,[13] robotic locomotor devices can increase the delivery of locomotor training by reducing the number of therapists and the potential physical effort required to facilitate human gait kinematics. Considering the potential benefits and limitations, a progression of locomotor training can incorporate robotic devices in the rehabilitation of people with incomplete SCI (see also Behrman and Harkema[8] and Behrman et al[31]). In people with significant paresis following SCI, specifically those who require multiple therapists to provide manually assisted locomotor training, providing passively guided movements may provide many of the afferent cues thought to be necessary to reestablish appropriate walking patterns while reducing therapists' labor. However, as demonstrated in the present study, instructions to use maximum voluntary effort with visual feedback may be required during robotic-assisted walking to achieve metabolic costs and hip flexor EMG activity similar to those associated with therapist-assisted walking.

As people improve voluntary control and require less assistance from therapists during treadmill stepping, the restraints of the robotic device may limit the generation of appropriate muscle activity patterns. By gradually transitioning subjects from robotic- to therapist-assisted training when possible,[13] appropriate muscle activity and associated metabolic costs may be achieved by increasing the voluntary effort required to step and maintain postural stability independently or with minimal assistance. With future advances in robotic devices that allow for compliant assistance or reduced guidance of leg swing[56] and manipulation of propulsive and lateral stabilization forces, robotic training may mimic more precisely the assistance provided by therapists during treadmill stepping. Until such devices are available, a transition from robotic- to therapist-assisted training with a treadmill and BWS likely is required to enhance the therapeutic benefits of locomotor rehabilitative strategies.

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