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High-Intensity Variable Stepping Training in Patients with Motor Incomplete Spinal Cord Injury: A Case Series

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Abstract

Background and Purpose: Previous data suggest that large amounts of high-intensity stepping training in variable contexts (tasks and environments) may improve locomotor function, aerobic capacity, and treadmill gait kinematics in individuals poststroke. Whether similar training strategies are tolerated and efficacious for patients with other acute-onset neurological diagnoses, such as motor incomplete spinal cord injury (iSCI), is unknown. Individuals with iSCI potentially have greater bilateral impairments. This case series evaluated the feasibility and preliminary short- and long-term efficacy of high-intensity variable stepping practice in ambulatory participants for more than 1 year post-iSCI.

Case Series Description: Four participants with iSCI (neurological levels C5-T3) completed up to 40 one-hour sessions over 3 to 4 months. Stepping training in variable contexts was performed at up to 85% maximum predicted heart rate, with feasibility measures of patient tolerance, total steps/session, and intensity of training. Clinical measures of locomotor function, balance, peak metabolic capacity, and gait kinematics during graded treadmill assessments were performed at baseline and posttraining, with more than 1-year follow-up.

Outcomes: Participants completed 24 to 40 sessions over 8 to 15 weeks, averaging 2222 ± 653 steps per session, with primary adverse events of fatigue and muscle soreness. Modest improvements in locomotor capacity where observed at posttraining, with variable changes in lower extremity kinematics during treadmill walking.

Discussion: High-intensity, variable stepping training was feasible and tolerated by participants with iSCI although only modest gains in gait function or quality were observed. The utility of this intervention in patients with more profound impairments may be limited.

Video Abstract available for more insights from the authors (see Video, Supplemental Digital Content 1, http://links.lww.com/JNPT/A200)

INTRODUCTION

Recovery of independent walking function is often a primary goal of individuals following spinal cord injury (SCI).[1] In individuals with motor incomplete SCI (iSCI), indicating partial preservation of supraspinal pathways, such recovery may be possible, although residual impairments in strength, postural control, and coordination often contribute to reduced gait speeds and aberrant gait kinematics (ie, quality).[2,3] Training strategies used to treat locomotor dysfunction vary and often include exercises to address underlying impairments, such as strength, balance, and flexibility training, in addition to stepping practice provided on a treadmill (TM) or overground. In many studies, a common goal of interventions is to facilitate normal kinematic patterns using therapist- or robotic-assistance in part to provide afferent input related to stepping[4–6] through optimizing sensory cues, posture, and kinematics.[7] However, the efficacy of these strategies for improving locomotor function or quality beyond conventional approaches is unclear,[8–12] as previous studies in participants with iSCI demonstrate negligible differences among exercise/training approaches.

Recent data from studies of participants with other neurological diagnoses other than SCI (ie, stroke[13,14]) indicate that exercise interventions that emphasize combined application of specific training parameters that influence neuromuscular and cardiovascular function may further augment locomotor recovery.[15,16] For example, providing large amounts of stepping practice has been shown to elicit gains in walking function, although walking practice alone and without consideration of other factors is not sufficient.[8,10,17] Recent data in individuals with hemiparesis poststroke suggest that providing stepping training in variable contexts (tasks or environments), particularly at higher aerobic intensities, can facilitate gains in walking and nonwalking behaviors as compared with an equivalent number of conventional therapy sessions.[14,18,19] The exclusive focus on stepping training at up to 85% of age-predicted maximum heart rate (HR) was designed to maximize the amount of stepping practice while simultaneously increasing the neuromuscular and cardiovascular demands of that practice.[13] In addition, stepping practice in variable contexts (ie, tasks or environments) was provided, which has been shown in animal models to facilitate greater gains in locomotor function than more traditional TM stepping.[20,21] In humans with neurological injury, stepping in multiple contexts (eg, TM overground, over stairs, and over or around obstacles) may mimic stepping conditions that may be encountered in the community settings and may allow for more rapid adaptation to real-world environments.[14,18,19] Application of this training paradigm without focusing on normalizing gait kinematics resulted in substantial gains in locomotor function in poststroke participants, with additional improvements in strength, balance, transfers,[14,19] aerobic capacity,[22] and selected kinematic patterns during overground or treadmill stepping.[14,23]

Despite the positive findings of prior locomotor training studies, the feasibility and efficacy of this intervention in individuals with other neurological diagnoses, including iSCI, have not been assessed. To date, previous studies have assessed the effects of variable task practice of skilled walking tasks in iSCI, although with less attention toward intensity.[17,24] Specific data[24]indicated that stepping training of variable, skilled walking tasks may lead to greater changes in walking function, due in part to greater recruitment of neural pathways involved in skilled movement. However, a subsequent study[17] revealed greater benefits from large amounts of TM stepping as compared with variable skilled walking training. A potentially important finding was that greater amounts of stepping practice and higher HRs were observed in the TM training groups, and the combined increases in stepping amount and intensity may have resulted in differences in outcomes[17] as suggested previously.[14,16,18] No studies to date have attempted to combine the training parameters of large amounts of practice at high aerobic intensities, while targeting variable walking skills in iSCI.

The rationale for applying similar training strategies in individuals with acute-onset central neurological injury with different etiologies (ie, stroke, SCI and brain injury) has been articulated previously.[25] The primary argument is that many of these disorders share commonalities in the pathways and mechanisms underlying motor adaptation and learning. Improved motor performance following training may, therefore, rely on plastic changes in spared neural networks in each disease condition, as opposed to discrete mechanisms within separate diagnoses. Nonetheless, application of this high-intensity variable stepping training to individuals with iSCI represents a separate set of challenges. For example, impairments following iSCI are bilateral and often more substantial, and volitional access to residual neural pathways subserving motor learning may be more limited. Furthermore, the resources required for delivering this training safely may be limited in individuals with greater impairments post-iSCI. Finally, increased risk of adverse events, such as autonomic dysreflexia during higher exercise intensities,[26] could complicate safe delivery of this intervention in individuals with iSCI.

The purpose of this case series was to investigate the feasibility and outcomes of a high-intensity variable stepping training on locomotor function and TM walking kinematics in ambulatory individuals with motor iSCI. Individuals more than 1 year following iSCI were recruited to participate in 8 weeks (up to 40 sessions) of walking training. Measures of feasibility included number of sessions attended, total stepping activity, and average intensity achieved during sessions, in addition to observed adverse events (eg, complaints of pain, fatigue, orthopedic injury, number of falls). We anticipated that a smaller amount of stepping practice would be achieved in individuals with iSCI versus stroke due to bilateral motor impairments, although we anticipated that reaching high-aerobic intensities such that positive gains in both function and gait quality would be demonstrated. Assessing the feasibility and preliminary efficacy of the effects of this training paradigm may provide insight into the potential challenges and benefits for future clinical investigations.

METHODS

Participants

Individuals with chronic iSCI (>1 year duration) were consecutively recruited via therapist referral from local outpatient rehabilitation centers and online research registries. Eligible participants were required to walk 10 m without physical assistance but with assistive devices and bracing below the knee as needed. All participants had to demonstrate lower extremity passive range of motion (ROM) of 0° to 30° plantar flexion, 0° to 60° of knee flexion, and 0° to 30° of hip flexion, and required medical clearance to participate. Exclusion criteria consisted of history of recent fractures or significant osteoporosis, cardiovascular instability, additional central or peripheral nervous system injury, and inability to adhere to protocol requirements, including attending training and testing sessions and not concurrently enrolled in physical therapyor other research interventions that focused on mobility or balance. Participants were encouraged to continue their normal everyday activities, and their subjective report of mobility in the community was obtained (ie, household or community ambulators). The project was approved by the local ethics committee and all participants provided written informed consent.

Outcome Measures

Participants were tested prior to (*pre*) and following (*post*) up to 40 training sessions as possible, with follow-up assessments at least 1 year posttraining. Feasibility outcomes were collected during training sessions and included number of steps per session and peak HRs and ratings of perceived exertion (RPEs) achieved during training, which appear to be important training variables that may influence locomotor recovery during physical interventions.[13,14,18,27] Additional measures of feasibility included the number of therapists/personnel required to safely deliver the training interventions and the number and type of potential adverse events, including falls within and outside of training sessions, signs/symptoms of autonomic dysreflexia (eg, rapid blood pressure increases), orthopedic injury, complaints of pain or soreness, or excessive fatigue.

Primary clinical outcomes were collected at *pre*, *post*, and follow-up, with testing completed by one of the research therapists. Primary walking outcomes included gait speed over short distances, with 2 trials averaged at self-selected speeds (SSS) and fastest-possible speeds (FS; GaitMat, Chalfont, Pennsylvania), and gait distance using the 6-minute walk distance (6MWD) with instructions to walk at participants' SSS. All participants used their customary assistive devices and bracing without physical assistance; if physical assistance was required with loss of balance, the tests were terminated and speed and distance documented. Secondary measures included the Berg Balance Score (BBS), as well as peak TM speed, peak oxygen uptake (), and lower extremity kinematics collected during graded TM testing (the latter collected only at *pre*-and *posttesting*) with simultaneous collection of metabolic and kinematic data to improve efficiency). Graded TM testing was performed on an instrumented force TM (Bertec Corporation, Columbus, Ohio), during which participants walked at 0.1 m/s, with speeds increased 0.1 m/s every 2 minutes. Participants wore a safety harness without weight support in case of loss of balance, with use of handrails as needed. Heart rate was evaluated continuously using a pulse oximeter (Masimo, Irvine, California) and the HR and RPE were recorded manually during the last 30 seconds of each minute. Peak TM speed was determined when there was a significant loss of balance, the participant requested to stop, or participants' HR was within 10 beats of their age-predicted maximum and RPE = 20.[28]

Kinematic data collected during graded TM testing were evaluated using an 8-camera motion capture system (Motion Analysis Corporation, Santa Rosa, California) and 32 reflective markers affixed bilaterally to each participant's pelvis and lower limbs to create a modified Cleveland Clinic 6-*df* model. Kinematic and kinetic data were sampled at a 100 Hz, processed using Cortex software (Motion Analysis Corporation, Santa Rosa, California), and further analyzed using custom software (C-Motion Incorporated, Germantown, Maryland; Mathworks, Inc, Natick, Massachusetts). Marker and force data for all walking trials were filtered using a low-pass second-order Butterworth filter, with a cutoff frequency of 10 Hz.

Joint excursions and spatiotemporal measures were calculated from the transformation between the respective model segments. Stance and swing phases of the gait cycle (GC) were identified bilaterally for all data. Stance was identified as the period when vertical ground reaction force signal crossed a minimum threshold of 25N. Instances where participants took steps that crossed both belts, kinematic events were utilized to define heel strike and toe off. The maximum anterior position of the calcaneal marker and the maximum posterior position of the metatarsal marker identified heel strike and toe off, respectively. Kinematic measures were normalized to percent GC and average step cycle profiles created. Spatiotemporal metrics were extracted during stance and swing phases, with primary measures of peak gait speed, stride length, and cadence. Specific joint kinematics outcomes included bilateral total joint ROM for the ankle, knee, and hip. Consistency of intralimb kinematics was utilized to estimate movement coordination between the hip and knee joints and calculated using the average coefficient of consistency (ACC).[29,30] The ACC utilized a vector coding technique, which was applied to frame-by-frame to the hip-knee angle-angle plots. The change in hip-knee angles from each frame to frame was represented as a vector, which averaged across multiple GCs, and the coefficient of correlation for each frame of the GC was determined. The ACC was calculated by the mean of the correlations for each frame-to-frame interval; ACC values close to 1 indicated greater consistency, with 0 indicating no consistency.

Intervention

Participants were scheduled to receive up to 40 sessions at 3 to 5 times per week within 10 weeks.[14,18] Individuals wore validated, reliable accelerometers on the ankle of their weaker leg during training sessions to estimate total amount of stepping practice. Each 1-hour session allowed up to 40 minutes of stepping training in variable contexts at the targeted intensity,[14,18] with rest breaks as needed. Successful stepping was defined as maintaining upright posture (ie, no hip or knee buckling, frontal and sagittal plane stability), moving in a specific direction (forward, backward, sideway), and generating bilateral positive step lengths. Orthotics and bracing were utilized as needed to prevent musculoskeletal injury (ie, ankle inversion or knee hyperextension), although bracing to minimize knee buckling was not permitted. Targeted training intensities were up to 85% of age-predicted maximum HR (ie, HR_{max}= 208 – [0.7 × age]) and evaluated continuously with a pulse oximeter. The minimum HR threshold for high-intensity training was set at 70% age-predicted maximum HR, consistent with previous published guidelines for high- or “vigorous”-intensity training[31,32] (see, however, Billinger et al[33]). In addition, subjective reports of intensity were obtained using the RPE scale,[34]with target intensities of 15 to 18. Both RPEs and HRs were recorded every 3 to 5 minutes.

Training sessions were supervised by a single physical therapist, with assistance from another research aide as needed. During the first 2 weeks (6-10 sessions), only forward stepping on a motorized TM (speed-dependent TM training) was performed to allow participants to accommodate to the large volumes of stepping at higher cardiovascular intensities. Minimal body weight support and handrail support were provided only as needed; only 1 participant was provided less than 10% body weight support and unilateral physical assistance for lower extremity advancement in the first week. There was no additional assistance provided to normalize kinematic patterns other than to simply continue stepping.[18]

Training over the remaining weeks was divided into 10-minute increments of speed-dependent TM training (described previously), skill-dependent TM training, overground training, and stair climbing, while trying to maintain the targeted HR range. Skill-dependent TM training included activities such as stepping in different directions (sideward or backward), applied perturbations to challenge various aspects of stepping (limb swing, propulsion, upright, lateral stability) in the form of obstacles and/or weights on the trunk or limbs, limiting use of upper extremities, or inclined surfaces. Participants practiced 2 to 5 different physical tasks that were randomly alternated and repeated within each 10-minute period; tasks were selected by the therapist on the basis of the individual's impairments and gait limitations, with consideration of participant preferences. For example, in individuals with difficulty with sagittal or frontal plane stability during walking and standing, practice focused on tasks that challenged dynamic stability, including walking without handrail support in multiple directions or on an inclined surface. Conversely, if participants demonstrated difficulty with limb advancement, leg weights were applied if the participant could continue stepping or focus directed toward stepping over obstacles or up an inclined TM. If a participant was unsuccessful during 3 to 5 consecutive attempts of a stepping task, task difficulty was reduced or physical assistance was provided.

Overground training focused on fast speeds and variable tasks as described previously, including walking over compliant, uneven, or narrow surfaces, and/or in different directions. Therapists used an overhead rail system or gait belt as needed for safety during overground stepping. Stair climbing was performed over static or rotating stairs with the use of an overhead catch system or a gait belt as deemed appropriate by the training therapist. The difficulty and intensity of stair negotiation were progressed by increasing speeds and reducing handrail support. If participants reported specific locomotor deficits or difficulties that limited their mobility, attention was directed toward these tasks (eg, limitation in community mobility may be addressed with obstacle avoidance tasks during overground walking, including stepping over or around objects, use of leg weights, or stepping on inclined surfaces). Therapists documented total amount of stepping activity during training sessions.

Data Analyses

The measures of feasibility and efficacy are detailed both individually and grouped throughout the text and in tables as means ± standard deviations. Measures of feasibility included the amount of stepping activity achieved during training and the ability to achieve training HRs or RPEs (maximum HR/RPE per session). Other measures of feasibility, including personnel required during training and potential adverse events, were documented descriptively. Primary and secondary outcomes include measures of gait speed, distance, balance, peak metabolic capacity, and gait kinematics as described previously. Because this is a case series, descriptive but not inferential statistical analyses are utilized, although comparisons are made to available data in other studies and as compared with minimally detectable changes and minimal clinically important differences in iSCI.

RESULTS

Feasibility

Five individuals with a history of chronic iSCI were referred consecutively from outpatient physical therapists and met all inclusion criteria. One potential participant did not receive medical clearance from their physician and was not enrolled. Demographic and clinical characteristics of the 4 participants (S1-S4) who initiated training are depicted in Table 1, indicating the variability in age (18-48 years) and duration post-SCI (14-53 months). Participants S1, S2, and S3 presented with substantial motor impairments, including relatively low values for Lower Extremity Motor Scores (LEMS; range: 21-34 pts), BBS (5-9 points), and slower gaits speeds (Table 2), particularly as compared with S4 who performed at a higher functional level. Participants S1 and S3 wore articulating ankle-foot orthoses (AFOs) bilaterally, and all 3 walked with a walker for shorter, that is, household distances, with community mobility accomplished using a wheelchair. In contrast, participant S4 did not use any assistive devices or braces and never used a wheelchair for home or community mobility.

Table 1. Baseline Demographics, Clinical Characteristics, and Training Parameters of Enrolled Participants

	Participant 1	**Participant 2**	**Participant 3**	**Participant 4**
Demographics/Clinical characteristics				
Age, y	34	45	48	18
Duration, mo	16	53	17	14
Gender	M	M	M	F
AIS classification	D	C	C	D
Neurologic level	C5	C7	T3	C5
LEMS	34	30	21	38
Assistive devices	Rolling walker	Walker	Walker	None
Bracing	Bilateral AFOs	None	Bilateral AFOs	None
Medications	80-mg baclofen	None	10-mg baclofen	None
Training parameters				
No. sessions	40	24	38	40
Steps per session (min-max)	1963 ± 189 (1586-2242)	1795 ± 190 (1360-1984)	1932 ± 206 (1475-2284)	3195 ± 354 (2342-3698)
%HRmax (min-max)	72 ± 4.1% (63%-79%)	65 ± 2.8% (57%-70%)	80 ± 4.2% (67%-88%)	83 ± 3.9% (72%-92%)
RPE (min-max)	18 ± 1.2 (15-19)	18 ± 1.3 (16-20)	17 ± 1.0 (15-19)	19 ± 1.1 (16-20)

Abbreviations: AFOs, ankle foot orthoses; AIS, American Spinal Injury Association Impairment Scale; HR, heart rate; LEMS, Lower Extremity Motor Scores; RPE, rating of perceived exertion.

Table 2. Pretraining, Posttraining, and Follow-up Outcomes for Primary and Secondary Clinical Assessments

	Participant 1			**Participant 2**			**Participant 3**			**Participant 4**		
	Pre	**Post**	**Follow-up**	**Pre**	**Post**	**Follow-up**	**Pre**	**Post**	**Follow-up**	**Pre**	**Post**	**Follow-up**
Primary												
SSS (m/s)	0.22	0.26	0.24	0.10	0.19	. . .	0.13	0.18	0.12	1.02	1.25	0.99
FS (m/s)	0.29	0.36	0.36	0.10	0.26	. . .	0.16	0.27	0.15	1.53	1.64	1.37
6MWD (m)	76	87	91	35	64	. . .	34	80	31	432	509	433
Secondary												
BBS	9	12	15	8	12	. . .	5	7	6	51	53	51
Peak TM speed (m/s)	0.50	0.60	0.50	0.20	0.50	. . .	0.10	0.30	0.10	1.2	1.3	1.3
$\dot{V}O_{2peak}$ (mL/kg/min)	26	30	17	17	23	. . .	19	22	11	25	29	23

Abbreviations: BBS, Berg Balance Score; FS, fastest-possible speeds; 6MWD, 6-minute walk distance; SSS, self-selected speeds; TM, treadmill.

Over the course of the intervention, participants S1, S3, and S4 completed 24 to 40 sessions of training within 10 weeks, while participant S2 required 15 weeks to complete training secondary to illness (ie, influenza). During each session, overhead harness safety systems were used for all participants in case of loss of balance and physical assistance from an aide was necessary for participants S1, S2, and S3, particularly early after the initiation of training and during stair climbing to ensure safety and adherence to protocol (ie, attempts at reciprocal stepping). Only participant S2 required approximately 10% body weight support early during training, which was reduced by the end of 2 weeks. Training parameters achieved are also presented in Table 1 for each participant, indicating the mean and standard deviations of peak HRs and RPEs, as well as the minimum and maximum peak values throughout training. All participants were able to achieve at least 70% of HR_{max} and RPEs of more than 15 during the first training session, although in participants S1 and SR HR responses were blunted across training. Peak HRs achieved during sessions averaged between 65% and 83% of age-predicted HR_{max}, while peak RPEs ranged from 17 to 19.

Following an initial warm-up period and delay in HR increases early during training, all participants were able to maintain their HRs within approximately 5% of this peak HR_{max} achieved each session, although only participants S3 and S4 were consistently able to achieve more than 70% predicted HR_{max}throughout training sessions. Participants took an average of 2222 ± 653 steps per session (range: 1795-3197) throughout training, with the largest amounts of practice in the participant S4. There were no reports of orthopedic injury or pain other than muscle soreness during the first 2 to 3 weeks, with the exception of low back pain reported by participant S2 that did not restrict participation. There were no additional adverse events, including no falls during or outside of training, or episodes of hypertension or autonomic dysreflexia. All but 1 participant reported fatigue during the period of training that subsided within the first 3 weeks, with the exception of participant S2 who reported fatigue intermittently throughout training. Participants S1, S3, and S4 were available to complete follow-up assessments, all 3 indicated attempts to maintain exercise programs at local gyms or at home following training.

Clinical and Metabolic Testing Outcomes

Changes in locomotor and other clinical measures for each participant are presented in Table 2. Changes in walking function included mean improvements in SSS (0.10 ± 0.09 m/s), FS (0.11 ± 0.03 m/s), and 6MWD (41 ± 28 m). Additional secondary assessments included increases in BBS of 2.8 ± 0.96, as well as increases in peak TM speed (0.18 ± 0.10 m/s) and (4.3 ± 1.5 mL/kg/min). In the participants who attended follow-up testing (S1, S3, and S4), gains were not maintained at least 1 year following training, with all clinical outcomes similar to pretraining assessments.

Kinematic Outcomes

Secondary analyses of TM gait kinematics were performed on all participants at *pre* and *post*. Immediately following training, all participants demonstrated changes in stride length (S1), cadence (S4), or both (S2 and S3) to accommodate for changes in peak TM speeds, with the largest relative changes in S2. Sagittal-plane joint angular excursions were, however, variable across the participants. Ankle, knee, and hip ROM increased minimally or up to 20° on the less impaired limb across participants, while changes in the more impaired limb were smaller. Compared with the other participants, larger changes in hip ROM were observed in S1 and S3 (both of whom wore AFOs during testing). However, there were no consistent trends for changes in joint or spatiotemporal kinematics.

Changes in gait quality during TM walking were evaluated using ACC values to estimate hip-knee coordination, which also demonstrated inconsistent changes across participants. Specifically, bilateral improvements in ACC were observed in S2 (0.07 and 0.17 in less and more impaired limbs), although very little changes were observed for S1 and S4. In contrast, bilateral decreases in ACC were observed in S3 (0.07-0.09), despite large changes in stride length and hip ROM (Table 3).

Table 3. Changes in Selected Gait Kinematics Pre- and Posttraining

	Participant 1		Participant 2		Participant 3		Participant 4	
Spatiotemporal								
Speed (m/s)	0.50	0.60	0.20	0.50	0.10	0.30	1.2	1.3
Stride length (m)	1.2	1.5	0.7	1.1	0.5	0.9	1.5	1.4
Cadence (steps/min)	51	51	37	57	24	46	100	111
Less impaired								
Ankle ROM (◦)	40	45	14	18	16	38	34	36
Knee ROM (◦)	81	85	73	68	47	50	46	61
Hip ROM (◦)	60	70	49	48	29	42	55	58
ACC	0.95	0.95	0.79	0.86	0.61	0.52	0.89	0.87
More impaired								
Ankle ROM (◦)	38	43	21	22	11	13	18	19
Knee ROM (◦)	79	72	73	68	26	25	29	26
Hip ROM (◦)	66	65	36	38	17	30	46	48
ACC	0.88	0.84	0.62	0.79	0.54	0.47	0.89	0.96

Abbreviations: ACC, average coefficient of consistency; ROM, range of motion.

DISCUSSION

The present case series details the potential feasibility and resultant locomotor, metabolic, and kinematic outcomes in 4 participants with chronic iSCI following high-intensity variable stepping training. Following the interventions, participants demonstrated modest improvements in selected outcomes, including gains in clinical measures of walking function, balance, and metabolic function, with improvements in selected measures of TM-based locomotor kinematics. The protocol appeared to be safe, resulting in no substantial adverse events and limited complaints of fatigue and soreness, with the exception of 1 participant. The protocol appeared to be feasible with the assistance of a therapist and an aide, with specific equipment such as harness support systems or bracing to allow safe training.

Average stepping activity during high-intensity training prioritized in this intervention (~2200 steps per sessions) was greater than published amounts of stepping activity observed during clinical treatment of patients with neurological injury.[35] These values are, however, lower than average stepping recorded in participants with subacute or chronic stroke who underwent similar training protocols (2500-3000 steps per session), some of whom were nonambulatory at the beginning of training.[14,18] The present data are likely influenced by the 3 substantially impaired participants with iSCI (S1, S2, and S3) in whom stepping activity averaged less than 2000 steps per session, despite maintaining moderate to high aerobic intensities. Improvements in primary measures were also limited in the 3 participants who had greater impairment and varied among all participants. Two individuals (S3 and S4) demonstrated changes that exceeded the reported minimal detectable change scores for 6MWD (ie, 46 m),[36] while three-fourths of participants (S1, S2, and S3) exceeded the minimal detectable change for SSS and FS utilizing changes relative to an individual's initial walking speed.[37] Finally, small gains in BBS were observed in all participants, regardless of extent of initial disability. The combined changes in locomotion and balance were similar to those observed in recent trials investigating the effects of various forms of locomotor training in participants with Isci,[10,38] including strategies of focused TM training or variable stepping activity performed overground.[17]Nonetheless, observed changes were relatively small as compared with data from participants with chronic stroke following a similar training protocol (eg, SSS: 0.23 ± 17 m/s; FS: 0.39 ± 0.23 m/s; 6MWD: 89 ± 60 m).[18]

During graded exercise testing, both peak TM speeds and increased consistently across participants. The average gains of 2 to 6 mL/kg/min in and 0.1 to 0.3 m/s in peak TM speeds approximate changes were observed in participants with chronic stroke or SCI following higher-intensity TM training[39–41] and gains in participants with iSCI following lower-intensity, recumbent stepping training.[42] While the data suggest some functional benefits of high-intensity training, kinematic analyses were utilized to provide some insight into strategies used to increase walking speed. Participants in this case series demonstrated improvements in stride length (S1), cadence (S4), or both (S2 and S3) to achieve higher TM speeds following training. Improvements in spatiotemporal measures were larger than changes obtained during overground stepping following different locomotor strategies, although the speed increases during TM testing likely account for these differences. The increases in stride length in 3 participants (S...) are of particular interest as previous data in iSCI suggested that increases in TM speeds are accomplished primarily using cadence,[43] with smaller changes in stride length (see, however, Leech et al[40]). Participants described in the former study were able to walk at faster speeds, similar to our higher functioning participant, who demonstrated limited gains in stride length (S4). The current findings suggest that individuals with iSCI, particularly those with lower levels of functioning, may be able to modulate both stride length and frequency with training to reach higher velocities.[40]

Consistent with the aforementioned and previous findings,[28] evaluation of joint kinematics during TM walking revealed changes primarily in those participants who demonstrated increases in stride length, namely, increased hip ROM was observed in at least 2 participants (S1 and S3) to account for changes in peak speeds, with limited or variable changes in knee and ankle ROM across all participants. These specific differences in hip ROM may be expected, as both S1 and S3 required AFOs during testing. Given the restriction of ankle motion and reduced propulsive forces generated by the plantar flexors with AFO use, increases in hip ROM could reflect compensatory strategies used to increase gait speed.[44] However, gait speed changes were similar in participants who did not wear AFOs, and biomechanical strategies appear to differ from those with lower extremity bracing. Unfortunately, we were not able to collect accurate gait kinetics during testing because of foot placement, and such analyses in future studies would provide further insight into the biomechanical mechanisms of increased speeds.

A surprising kinematic finding was the lack of improvements in hip-knee angular consistency following training. Previous data in participants with stroke[23] or incomplete SCI[40,45] following higher-intensity stepping protocols demonstrate improvements in ACC, although other stepping protocols that may not focus on high cardiovascular intensities elicit variable changes in intralimb consistency.[45] The inconsistent changes in ACC do not appear to be due to limited changes in speed, as participants with similar speed improvements demonstrated both positive and negative ACC changes (eg, S2 and S3). Interestingly, the participant with large decreases in ACC bilaterally (S3) was the most impaired, as indicated by lower LEMS (21) and BBS (5) at baseline. Conversely, while S2 presented with equivalent initial walking speed as S3 at baseline, S2 demonstrated a higher LEMS and the largest gains in ACC values. Perhaps individuals with more severe motor deficits utilize alternative and inconsistent compensatory strategies to advance the limbs during stepping tasks, whereas those with greater motor control may be able to demonstrate greater intralimb consistency and coordination with improvements in gait speed with training. Greater sample sizes in future studies may help elucidate the validity of this hypothesis.

Even with the modest improvements observed, none of the gains were maintained in the 3 participants tested at follow-up. Given the increased prevalence of cardiovascular disease and diabetes mellitus in persons with SCI,[46] lower peak metabolic capacity,[40,47] and reduced daily stepping,[2]additional interventions of physical activity are likely necessary to maintain gains in motor function following interventions. Selected reports have elucidated the positive effects of cardiovascular gains when training walking ability,[10,48] with a recent systematic review reporting a low risk of cardiovascular training when conducted with proper safety precautions.[49]Given reduced access to such interventions, community-based strategies to increase participation in high-intensity stepping training may be an effective way to maintain gains observed.

Limitations of our case series include lack of blinded assessors and potential testing effects contributing to the outcomes. In addition, while assessment of gait kinematics during TM testing may be similar to overground walking, the use of bilateral handrails could result in very different biomechanical strategies as compared with overground ambulation.[50] Furthermore, the small sample size and limited diversity of individuals of varying levels of impairment are specific limitations that may limit the ability to generalize these findings. More directly, 3 participants presented with fairly low LEMS and BBS scores (S1-S3) and could not achieve more than 2000 steps/session, and the benefits may be limited in very impaired individuals post-iSCI.[10]

A potentially important, related limitation is the inability to consistently achieve the desired HR range of at least 70% predicted HR_{max} during training in specific participants. For both S1 and S2, mean peak HRs were below or near 70% HR_{max} despite attempts to achieve up to 85% HR_{max}. Reduced HRs may be due to reduced afferent feedback with substantial deficits in volitional neuromuscular activation following SCI, or more likely decreased central drive to thoracic-level sympathetic neural circuits that innervate the heart.[51] Indeed, both S1 and S2 achieved lower average peak HRs and presented with cervical-level injuries and substantial motor impairments that may underlie the reduced central drive to increase HRs. Use of surrogate measures, such as RPEs, may assist in estimating exercise intensity; its use in individuals with SCI may also be limited[52] and may reflect other subjective measures. Whether the limited benefits observed in selected participants were due to the degree of neuromuscular impairments or limited cardiovascular regulation, or both, is not clear. Perhaps additional, adjunctive strategies, such as electrical stimulation of central neural tissues[53] to augment neuromuscular activation, may better facilitate gains and augment exercise intensity in individuals with lower functional capacity when paired with higher-intensity stepping strategies.

SUMMARY

The combined findings of this case series suggested modest improvement in locomotor function in individuals with motor iSCI with variable stepping training at high intensities, and emphasized the importance of assessing intervention strategies directly on a targeted clinical population. Gains in lower-functioning, ambulatory individuals with chronic iSCI may be more limited than anticipated, and comparable outcomes may be expected when similar strategies are applied in the clinic. Given these limitations, the potential benefits of high-intensity variable stepping training in this population is uncertain. Investigations that delineate changes in both locomotor function and quality across individuals with varying motor impairments will facilitate appropriate clinical implementation as warranted.

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Supplemental Digital Content

- JNPT_42_2_2018_01_29_HORNBY_JNPT-D-16-00149R4_SDC1.mp4; [Video] (23.45 MB)