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## Foot placement variability as a walking balance mechanism post-spinal cord injury

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### Abstract

**Background**—Spinal cord injury affects walking balance control, which necessitates methods to quantify balance ability. The purposes of this study were to 1) examine walking balance through foot placement variability post-injury; 2) assess the relationship between measures of variability and clinical balance assessments; and 3) determine if spatial parameter variability might be used as a clinical correlate for more complex balance measurements.

**Methods**—Ten persons with spinal cord injury walked without devices on a split-belt treadmill at self-selected speeds. Ten healthy controls walked at 0.3 and 0.6 m/s for comparison. Variability of step width and length, anteroposterior and mediolateral foot placements relative to center-of-mass,

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and margin-of-stability were calculated. Clinical assessments included Berg Balance Scale and Dynamic Gait Index.

**Findings**—Participants with spinal cord injury demonstrated significantly different variability in all biomechanical measures compared to controls ( $P \leq 0.007$ ). Berg Balance Scale scores were significantly inversely associated with step length as well as anteroposterior and mediolateral foot placement variability ( $P \leq 0.05$ ). Dynamic Gait Index scores were significantly inversely associated with mediolateral foot placement variability ( $P \leq 0.05$ ). Participants with spinal cord injury showed significant correlations between spatial parameter variability and all other measures ( $P \leq 0.005$ ), except between step length and margin-of-stability ( $P = 0.068$ ); controls revealed fewer correlations.

**Interpretation**—Persons post-spinal cord injury exhibit an abnormal amount of stepping variability when challenged to walk without devices, yet preserve the ability to avoid falling. When complex laboratory measures of variability are unavailable clinically, spatial parameter variability or standardized balance assessments may be plausible indicators of walking balance control.

## Keywords

spinal cord injury; walking; balance; margin of stability; variability

## 1. Introduction

Balance control requires both upright posture and equilibrium to achieve functional ambulation and avoid falling (Macpherson et al., 1997). Persons with spinal cord injury (SCI) report balance dysfunction as a contributor to the high falls incidence and secondary injuries seen in this population (Brotherton et al., 2007). Spinal cord lesions often affect the sensorimotor systems involved in balance control, thus creating precarious walking conditions prone to falls (van Hedel et al., 2005, Shumway-Cook and Woollacott, 2001). This susceptibility to falls is even more pronounced when individuals who typically walk with compensatory assistive devices attempt to walk without them. In order to rehabilitate loss of balance control, measurement tools that can quantify distinctive balance strategies of the SCI population are necessary to understand the effectiveness of interventions as well as an individual's progress over time.

Clinicians commonly document the quality of spatial parameters at the feet, such as “wide base-of-support” when observing an increased step width, to describe the stability in a person's walking pattern. However, these clinical observations do not describe the dynamic control of the body's center-of-mass (CoM). As walking progresses forward, the CoM accelerates past the single stance limb and causes the CoM to “fall” with each step. Consequently, precise placement of the contralateral swing foot is critical to recapture the falling CoM within the base of support (Patla et al., 1999). If the foot contacts the ground in a sub-optimal position, subsequent steps must adjust to compensate for this error, thus inducing small perturbations. Studies of soleus H-reflexes during healthy walking confirm the nervous system priority to control placement of the foot and ensure stability when balance is perturbed (Krauss and Misiaszek, 2007). Following SCI, each step during level overground walking could be viewed as its own potential perturbation to the neuromuscular system necessitating corrective foot placements.

Balasubramanian et al. (2010) further demonstrated that spatial parameters may not be associated with foot placement relative to the CoM in a neurologically-impaired population. While the authors reported a significant positive relationship between step length asymmetry and asymmetry in the anterior placement of the foot relative to the pelvic CoM in persons

post-stroke, no relationship existed between step width and the lateral placement of the foot relative to the CoM. This disparity between measures suggests that a clinical examination of foot-to-foot distances as an indicator of balance may not always reflect a person's true ability to control CoM motion through foot placements.

An additional measure has been developed in the laboratory to characterize balance control beyond spatial parameters and foot placement relative to the CoM. Given the dynamic nature of walking, an expansion of these static measurement approaches has been suggested to account for the impact of velocity on the CoM position during this task. Hof et al. proposed a measure called the margin of stability (MoS) (Hof et al., 2005). This measure compares the shortest mediolateral distance between the center-of-pressure (CoP) and the extrapolated center of mass (XcoM) during double limb support as weight acceptance begins (from initial contact of the leading limb to toe-off of the trailing limb). The XcoM is the vertical projection of the CoM in the direction of its velocity. If the CoM reaches the boundary of the CoP and continues to have an outwardly-directed velocity vector, a person must take a step to increase the base of support or a fall results.

From the clinic to the laboratory, three methods for quantifying walking balance have been described in a rather hierarchical manner, from basic locations of the feet to inclusion of the body-centric CoM and its velocity. Since persons with SCI may require step-to-step corrective foot placements to maintain stability in the face of sensorimotor impairments, one of the most important factors to consider in each of these measures is its variability. Thus, the primary purpose of this study was to investigate walking balance through variability in spatial parameters, foot placement relative to the CoM, and MoS in persons post-SCI. We aimed to understand how the variability of these measures differed between persons with SCI and healthy controls. Additionally, we sought to bridge the laboratory and clinical interpretations of balance by 1) examining the relationship between measures of variability and standardized clinical balance assessments, and 2) identifying the utility of spatial parameter variability as a potential clinical correlate for more complex measurements that incorporate CoM and XcoM. We specifically chose to study individuals who usually walked with an assistive device and/or physical assistance, but when devices and assistance were removed, they were still able to walk a few steps. For these individuals, study findings could provide a window into biomechanically *how* they were able to accomplish the task.

## 2. Methods

### 2.1 Participants

A convenience sample of 10 individuals with chronic, incomplete SCI (6 males; mean age 42.6 years (SD 14.2)) (Table 1) and 10 healthy persons comprising a control group (3 males; mean age 56.1 years (SD 3.3)) participated in this cross-sectional study. Participants with SCI were involved in a larger randomized controlled trial with the following inclusion criteria: 1) at least 18 years of age, 2) injury sustained at least 6 months prior to the study, 3) upper motor neuron, motor incomplete spinal cord lesion, 4) ability to ambulate at least 10m with or without an assistive device, and 5) injury of traumatic or non-traumatic origin, excluding those of congenital etiology. The subset of individuals selected for this study from the larger trial included those who could generate at least three steps *without* an assistive device, bodyweight support (BWS), or physical assistance during testing. The healthy adult controls were a convenience sample from a larger ongoing cross-sectional study. All controls were 18 years of age or older and full-time ambulators without assistive devices or physical assistance. All experimental procedures were conducted at the Brain Rehabilitation Research Center, Malcom G. Randall Veteran Affairs Medical Center in Gainesville, Florida. Each participant signed a written informed consent approved by both the VA

Subcommittee for Clinical Investigation and the University of Florida Health Science Center Institutional Review Board.

## 2.2 Experimental procedures

A licensed physical therapist assessed motor and sensory function in persons with SCI based on the American Spinal Injury Association International Standards for Neurological and Functional Classification of Spinal Cord Injury (Hadley, 2002, Ditunno et al., 2007, Marino et al., 2008). This assessment established SCI severity and categorized injuries according to the American Spinal Injury Association Impairment Scale (AIS). A physical therapist also assessed performance on standardized balance assessments: the Berg Balance Scale (BBS) (Berg et al., 1992) and the Dynamic Gait Index (DGI) (Jonsdottir and Cattaneo, 2007).

Both participants with SCI and healthy controls had reflective markers and rigid body clusters positioned on specified body landmarks to acquire 3D motion data. Marker positions were based on the Vicon PlugInGait marker set (modified Helen Hayes set). All individuals wore a safety harness attached to the laboratory ceiling. Walking trials lasted a maximum of 30 seconds and were performed over a split-belt instrumented treadmill (Tecmachine, Inc., Cedex, France). Walking practice was permitted to become accustomed to walking on the treadmill and to obtain the best possible steady-state walking speed. When comfortable, data collections commenced. Those individuals with SCI performed one walking trial during which they were instructed to walk to the best of their abilities at their self-selected (SS) treadmill speed. All walked *without* assistive devices or braces. In addition, although participants with SCI wore a safety harness for each trial should they have stumbled or fallen, neither BWS nor manual assistance was provided. This testing condition was intended to capture true walking capacity post-injury. Sitting or standing rest periods were provided as needed between bouts of activity. Healthy controls performed two separate walking trials at 0.3 and 0.6 m/s for normal comparisons to the speeds which persons with SCI elected to walk.

## 2.3 Data acquisition and processing

Twelve camera passive motion analysis (Vicon Motion Systems, Oxford, UK) and 3D ground reaction forces (GRFs) from each half of the treadmill were acquired continuously during walking trials. The split-belt treadmill system allowed collection of GRFs for each stance phase over multiple steps of the gait cycle. Raw kinematic data were collected at 100 Hz, then low-pass filtered using a fourth-order, zero-lag Butterworth filter with a 6 Hz cut-off frequency. GRFs were acquired at a sampling rate of 2000 Hz, and low-pass filtered using a fourth-order, zero-lag Butterworth filter with a 20 Hz cut-off frequency. A 13-segment musculoskeletal model was created using Visual 3D (V3D) processing (C-Motion, Inc., Germantown, MD, USA) that fit the model to marker trajectories in order to calculate kinematics of each segment. Custom Matlab programming (Mathworks, Inc., Natick, MA, USA) was developed to calculate the outcome measures described below.

## 2.4 Biomechanical outcome measures

Means were calculated from individual step data in a walking trial to indicate the average magnitude of each outcome for each person. Values for both right and left legs were entered into calculations for controls as well as those with SCI. Variability across each walking trial was calculated using standard deviations.

**2.4.1 Spatial and foot placement parameters**—Two spatial parameters and two foot placement parameters were calculated. The two spatial parameters were used to indicate the mediolateral (ML) and anteroposterior (AP) distances of one foot relative to the contralateral foot. The two foot placement parameters were used to indicate the ML and AP distances of

the foot relative to the “falling” body (Balasubramanian et al., 2010). Specifically, these four measures were defined as the following distances at each initial contact: 1) leading foot CoM to trailing foot CoM in the ML direction (“Step width”) and in the AP direction (“Step length”) and 2) leading foot CoM to pelvis CoM in the ML direction (“ML foot placement”) and in the AP direction (“AP foot placement”) (Figure 1).

**2.4.2 Margin of stability (MoS)**—Based on Hof and colleagues’ definition and equations (2005), MoS was calculated as the shortest perpendicular ML distance between the CoP and the extrapolated center-of-mass (XcoM) during double limb support (Figure 2). A larger MoS is consistent with increased stability as a greater boundary exists between the maximum XcoM and the CoP. Furthermore, the size of the margin is proportional to the impulse that would be required to destabilize or unbalance a person.

## 2.5 Data analysis

Means and standard deviations were calculated for all biomechanical measures. Using standard deviations for each person with SCI, standard differences from the control group walking at a matched speed were determined. Thus, the control group mean equaled zero, variance equaled one, and SCI values beyond  $\pm 2$  standardized scores were considered outliers. Speed matching was established as follows: SCI  $\leq 0.3$  m/s matched to controls at 0.3 m/s; and SCI  $> 0.3$  m/s to 0.6 m/s matched to controls at  $\leq 0.6$  m/s. Preliminary visual analysis of SCI standardized data indicated heterogeneity in the sample with variability in both positive and negative directions relative to controls. Therefore, to avoid masking true differences in the SCI sample and regressing SCI data toward a mean value, which might demonstrate no difference from controls, absolute values were calculated to determine a participant’s distance from a central point of zero. The mean of all participants’ absolute values was used to compare the SCI group and healthy individuals using a permutation test. Using non-standardized data, Pearson’s correlations investigated the relationships of 1) standardized balance assessments versus all measures of variability and 2) variability of spatial parameters versus foot placements and versus MoS in the SCI group and in controls at both treadmill speeds. Alpha level for significance was set at .05.

## 3. Results

### 3.1 Variability of biomechanical outcomes: SCI versus controls

For all five outcome measures, participants with SCI displayed significantly different variability from controls ( $P \leq 0.007$ ). Table 2 presents actual measured mean and standard deviation values for each outcome. Figure 3 shows standardized data for individual participants, which illustrate direction and magnitude of differences from a control mean of zero, in addition to the various combinations and degrees of variability across participants. The majority of participants exceeded +2 standardized scores for step width, step length, and ML and AP foot placement variability; in comparison, fewer participants with SCI exhibited MoS variability outside of this value. Values beyond +2 standardized scores demonstrate *greater* movement variability compared to the variability exhibited by healthy individuals. However, it should be noted that there were individuals with SCI in our sample (e.g. SCI3 in all five measures) who demonstrated negative deviations from the control mean (decreased variability). However, no participants presented values below  $-2$  standardized scores.

### 3.2 Associations between outcome variability and standardized balance assessments in SCI

Total BBS scores were significantly, negatively associated with three measures of variability: step length ( $r = -.638$ ,  $P = .047$ ) and both AP ( $r = -.696$ ,  $P = .025$ ) and ML ( $r = -.665$ ,  $P = .036$ ) foot placement. Total DGI scores demonstrated only one significant



correlation: a negative association with ML foot placement variability ( $r = -.700$ ,  $P = 0.024$ ). Higher BBS and DGI scores reflect greater balance ability.

### 3.3 Associations among outcome variability by group

At self-selected speeds, the SCI group displayed significant positive relationships between spatial parameter variabilities and all other measures. This was true regardless of movement direction and included the association between step width and step length themselves ( $r \geq 0.802$ ,  $P \leq 0.005$ ). The only exception was the relationship between MoS and step length variability, which just missed significance ( $r = 0.597$ ,  $P = 0.068$ ). Fewer associations were detected within the control group. At 0.3 m/s, only the step length and AP foot placement variability were significantly positively correlated ( $r = 0.913$ ,  $P = 0.0006$ ). Controls walking at 0.6 m/s also showed the same significant relationship as they did at the slower speed ( $r = 0.804$ ,  $P = 0.009$ ), but additionally exhibited a significant positive correlation for step width and ML foot placement ( $r = 0.632$ ,  $P = 0.05$ ).

## 4. Discussion

### 4.1 Spinal cord injury alters movement variability

To our knowledge, this is the first study to explore the intrinsic capacity for walking balance (i.e. without assistive devices) in persons with SCI using variability as an indicator of balance. Understanding the way individuals avoid falling by challenging them to engage affected trunk and limb muscles is compatible with the current shift in neurorehabilitation toward recovery of function (Behrman et al., 2006). Our comparison of persons post-SCI and healthy individuals revealed that an injury significantly changes the variability of step width, step length, ML and AP foot placements relative to the CoM, and MoS from normal values. Regardless of whether measurements were recorded simply between feet or whether they included the CoM and its velocity, variability across steps was abnormal after injury. Specifically, variability was higher than the normal range for many persons with SCI.

A debate exists in the scientific literature attempting to discern between “good” or “bad” movement variability. This discussion extends to the literature on balance (also referred to as stability) with efforts to determine if low variability equates with stability and high variability with instability or vice versa (van Emmerik and van Wegen, 2002). Research of physiological responses such as heart rhythms indicates that a certain degree of variability is normal and a lack of variability, or conversely too much variability, is pathologic (Glass, 2001). The same interpretation of variability can be applied to walking balance. Balance is based similarly on underlying physiological mechanisms, such as afferent feedback loops, only the result is motor output of the head, trunk, pelvis and extremities (Horak, 2006). While a certain level of variability is inherent in healthy individuals, research has described relationships of high and low stepping variability with balance deficits in elderly populations (Granata and Lockhart, 2008) and those with certain neurological disorders, such as normal pressure hydrocephalus (Stolze et al., 2000), respectively. Our analysis to evaluate differences in variability between the SCI and control groups allowed for consideration of a normal range of variability (i.e. comparison to a control group implicitly controls for the fact that even healthy individuals do not have perfectly consistent steps across a walking trial). Standardizing each person with SCI to the healthy group and controlling for treadmill speed detected deviations from a normal range (i.e. beyond  $\pm 2$  standardized scores).

To control CoM motion for walking balance, Dietz (2002) states that the afferent inputs weighted and selected by the central nervous system must meet the equilibrium requirements of that task. Furthermore, since SCIs interrupt the flow of sensory feedback to the supraspinal centers required for integration of information for balance, the ability of the

nervous system to appropriately select and utilize sensory information may be impaired. As a result, the motor output may contain errors, which continually require corrections. Additionally, Barbeau et al. (1999) reported several sensorimotor factors post-SCI that impact walking recovery, including walking balance. Muscular weakness and dyscoordination as well as hyperactive spinal reflexes were proposed factors. The presence of neuromuscular impairments such as these could feasibly alter the ability of an individual to produce a consistent series of steps, thus creating differences in variability from normal.

#### 4.2 Greater step variability relates to poorer balance assessment scores

Standardized balance assessments exhibited significant inverse relationships with certain measures of variability suggesting that the higher or more improved the scores on balance assessments, the less variable the spatial parameters or foot placements during walking. Any correlation between balance assessments and walking variability was unexpected because of the task-specific differences between the BBS (sitting and standing), DGI (gait with assistive devices), and treadmill walking condition without assistive devices. Even more interesting was the greater number of significant correlations detected between variability measures and BBS compared to DGI. One possible explanation may be that both the treadmill testing condition and the BBS assessed balance without assistive devices, which could be seen as more “recovery-based” than walking with assistive devices. Furthermore, SS walking speeds over the treadmill were remarkably slow (all but one person walked  $\leq 0.3$  m/s; Table 1). Post-hoc video observations revealed prolonged double limb support periods, which created several stationary, standing-like moments at the slower speeds. These observations could explain why, unlike other measures of variability, the more dynamic MoS showed no relationship to either balance scale.

#### 4.3 Spatial variability may be a good clinical correlate for balance

Our investigation also sought to understand the potential of spatial parameter variability to function as a clinical correlate for control of CoM motion by examining relationships between spatial parameter and foot placement parameter variabilities. In an earlier, unpublished analysis, our group correlated the magnitudes (rather than variability) of these measures for this exact sample of participants. Outcomes measured along the same plane (step width and ML foot placement as well as step length and AP foot placement) demonstrated positive associations in SCI and controls. For both groups, these relationships might have been one strategy by which individuals regulated control of the CoM. However, our challenge remained to determine why and quantify how persons with SCI were unstable as reflected by use of assistive devices for walking support (Table 1). Thus, we analyzed variability as a first step in addressing the need for a quantifiable measure of balance that could be collected in the clinic.

While literature exists that correlates the magnitudes of foot placement and spatial parameters (Balasubramanian et al., 2010, Hof et al., 2007), correlations of variabilities have not been examined until now. We showed that measures of variability exhibited a more extensive set of significant correlations for persons with SCI than for healthy controls at 0.3 or 0.6 m/s. Control data at either speed showed only one or two significant correlations; yet, persons with SCI showed significant positive associations in all measures, except between step length and MoS variabilities. The wide array of associations, irrespective of direction, suggests that individuals with SCI may avoid falling via a continuous pattern of step adaptations within a walking trial. Research demonstrates that healthy persons also exhibit a sequence of recovery steps when the lower extremities are perturbed (Oddsson et al., 2004). Purportedly, this recovery strategy is due to the nervous system’s automatic control to recapture CoM within the base of support. If each step in a person with SCI produces its own perturbation caused by step error, individuals could be attempting to correct for errors

one step after the next. Yet, the series of steps may be quite different in the combination of step lengths and step widths. On the contrary, the lack of multiple significant associations across variability measures in controls may indicate that they have the ability to control parameters in different directions independently (i.e. AP foot placement and step width) during level treadmill walking.

#### 4.4 Further clinical considerations within a recovery-based framework

Quantifying walking balance following SCI is essential to understand progression of an individual's function over time. However, the interpretation of the measurement tools implemented needs to be considered in light of the conditions under which an individual was evaluated. A unique feature of this study was the testing environment utilized to investigate walking balance. Having individuals with SCI walk in a safety harness while on a treadmill afforded them the opportunity to explore any immediate balance responses without the constraint of an assistive device. Thus, this testing condition created a recovery- or activity-based evaluation environment, which parallels the rehabilitation paradigm shift toward activity-based therapies (Dromerick et al., 2006). This is in contrast to conventional evaluation and treatment approaches, which allow an individual to compensate for impairments with assistive devices and produce different movement patterns than they would if devices were removed and upper extremities were unloaded. Leroux and colleagues (2006) also examined individuals with SCI without their assistive devices during walking on a treadmill in a harness. While they assessed the ability of an individual to adapt to walking on a treadmill at different inclines, our intentions were to examine balance responses during level ground walking and only to the perturbations induced by a person's individual walking pattern (i.e. without external perturbations or environmental changes during the task). Given this testing environment, the findings presented in this study should be carefully considered when attempting to translate to a clinical arena without such equipment capabilities. The potential exists that outcomes might have been different if individuals were walking with their customary assistive devices or overground rather than on a treadmill. However, in remaining consistent with the paradigm shift in neurorehabilitation, the outcomes presented here complement the transition toward activity-based therapies and can assist in understanding the effects of these therapeutic strategies and future efforts targeting recovery.

Because of the small sample size in this study, the generalization of findings is limited at this time. Yet, the findings do provide an opportunity to expand investigations in walking balance post-SCI. Another limitation is the small number of steps individuals with SCI walked during trials (range: 8–46 steps). The amount of walking was reduced because certain individuals could physically produce only a finite number of steps and were unable to generate additional steps during subsequent walking attempts. However, each individual's data provide information about his/her abilities specific to a distinctive injury. That is, how they accomplish the task of walking, when by all other accounts those who use assistive devices (particularly rolling walkers) would not be considered able to walk without them.

## 5. Conclusions

Whether examining only spatial parameters or foot placement relative to CoM and XcoM, persons after SCI exhibit a significantly different amount of variability (usually greater) compared to normal levels of variability. This increased variability may be a compensatory mechanism used to avoid falling during walking. Additionally, some of the increased variability related to diminished performance on certain balance assessments as well as to increased variability in the other biomechanical outcomes. Future investigations should continue to examine the variability of movements that individuals possess post-SCI as an indicator of balance control during walking. Specifically, additional studies are necessary that 1) evaluate controls at a greater range of speeds, 2) evaluate larger samples of both



controls and persons with SCI, and 3) determine specific cut-off values of normal variability for step widths and lengths to create a more efficient and clinically friendly interpretation of variability as a balance measurement tool. Understanding the repertoire of balance strategies in this population will assist clinicians in targeting therapies that address specific balance deficits.

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## Biographies

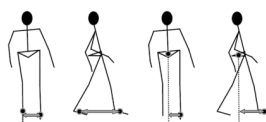
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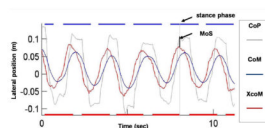
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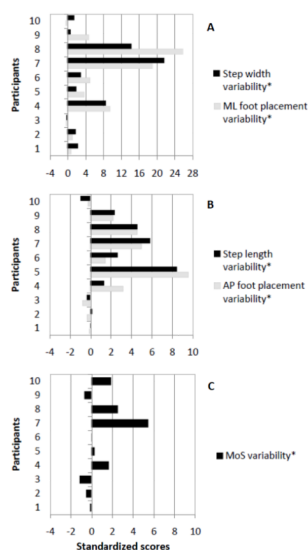
**Figure 1.**

Spatial parameters using foot-to-foot center-of-mass (CoM) distances and foot placements using foot CoM relative to pelvic CoM distances. From left to right, gray arrows represent the following measures: step width, step length, mediolateral foot placement, and anteroposterior foot placement. This representative schematic depicts SCI10 walking without a device with a left forefoot initial contact.



**Figure 2.**

Raw center-of-pressure (CoP), center-of-mass (CoM), and extrapolated center-of-mass (XCoM) trajectories. The vertical black line connecting the peak of the XCoM with the CoP represents the margin of stability (MoS) for a single step. The gray vertical line extending beyond the MoS distance illustrates the time in the gait cycle (end of double limb stance) when the shortest MoS occurred for that particular step.



**Figure 3.** Variability of standardized outcomes for individual participants with SCI. Values represent direction of deviation from the control mean of zero (variance=1). (A) Step width and mediolateral (ML) foot placement; (B) Step length and anteroposterior (AP) foot placement; (C) Margin of stability (MoS). (\*) indicates significant difference from controls at  $P \leq 0.05$ .



SCI participant demographics

Table 1

Participant	Age (yrs)	Sex	Injury site	Time post SCI (mos)	Assistive device	LEMS (max:50)	AIS	BBS (max:56)	DGI (max:24)	Self-selected treadmill speed (m/s)
SCI1	45	M	C5-6	10	RW	43	D	46	17	0.3
SCI2	55	M	C4	45	SPC	45	D	31	14	0.25
SCI3	48	F	C5	25.5	SPC	46	D	51	12	0.3
SCI4	26	M	T3-4	11	RW	40	D	21	15	0.15
SCI5	66	M	C7	78	SPC	49	D	48	17	0.5
SCI6	47	F	C4	6.5	RW	43	D	19	12	0.12
SCI7	40	F	T2-3	11	RW	38	D	10	9	0.2
SCI8	21	M	C6	7	RW	45	D	17	8	0.2
SCI9	27	M	T6	12	RW	40	D	12	11	0.03
SCI10	51	F	C4-5	7.5	SPC	45	D	42	14	0.25

LEMS: Lower Extremity Motor Score, AIS: American Spinal Injury Association Impairment Scale, BBS: Berg Balance Scale, DGI: Dynamic Gait Index, RW: Rolling Walker, SPC: Single Point Cane

**Table 2**

Measured biomechanical outcome values

Participants	Control group	speed match (m/s)	MoS Mean(SD)	Step Width Mean(SD)	Step Length Mean(SD)	ML Foot Placement Mean(SD)	AP Foot Placement Mean(SD)
SCI1	0.3		0.141(.025)	0.253(.015)	0.200(.034)	0.163(.010)	0.116(.024)
SCI2	0.3		0.164(.022)	0.256(.014)	0.140(.036)	0.160(.011)	0.101(.022)
SCI3	0.3		0.059(.018)	0.155(.010)	0.291(.030)	0.113(.008)	0.166(.019)
SCI4	0.3		0.087(.036)	0.180(.028)	0.139(.049)	0.115(.023)	0.040(.049)
SCI5	0.6		0.111(.025)	0.264(.020)	0.322(.075)	0.151(.015)	0.108(.046)
SCI6	0.3		0.085(.026)	0.193(.017)	0.125(.064)	0.115(.016)	0.045(.035)
SCI7	0.3		0.106(.059)	0.184(.056)	0.183(.098)	0.101(.036)	0.093(.062)
SCI8	0.3		0.099(.041)	0.213(.041)	0.224(.085)	0.134(.046)	0.077(.059)
SCI9	0.3		0.067(.021)	0.299(.012)	0.092(.060)	0.167(.016)	0.045(.041)
SCI10	0.3		0.087(.037)	0.198(.014)	0.248(.023)	0.142(.008)	0.057(.023)
Controls 0.3 m/s			0.083(.025)	0.225(.010)	0.258(.035)	0.146(.009)	0.143(.025)
Controls 0.6 m/s			0.110(.022)	0.196(.015)	0.359(.023)	0.118(.008)	0.198(.016)

MoS: Margin-of-stability, SD: standard deviation, ML: mediolateral, AP: anteroposterior