Variability of Leg Kinematics during Overground Walking in Persons with Chronic Incomplete Spinal Cord Injury

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Abstract

Incomplete spinal cord injury (iSCI) often leads to partial disruption of spinal pathways that are important for motor control of walking. Persons with iSCI present with deficits in walking ability in part because of inconsistent leg kinematics during stepping. Although kinematic variability is important for normal walking, growing evidence indicates that excessive variability may limit walking ability and increase reliance on assistive devices (AD) after iSCI. The purpose of this study was to assess the effects of iSCI-induced impairments on kinematic variability during overground walking. We hypothesized that iSCI results in greater variability of foot and joint displacement during overground walking compared with controls. We further hypothesized that variability is larger in persons with limited walking speed and greater reliance on ADs. To test these hypotheses, iSCI and control subjects walked overground. Kinematic variability was quantified as step-to-step foot placement variability (end-point), and variability in hip-knee, hip-ankle, and knee-ankle joint space (angular coefficient of correspondence [ACC]). We characterized sensitivity of kinematic variability to cadence, auditory cue, and AD. Supporting our hypothesis, persons with iSCI exhibited greater kinematic variability than controls, which scaled with deficits in overground walking speed ($p < 0.01$). Significant correlation between ACC and end-point variability, and with walking speed, indicates that both are markers of walking performance. Moreover, hip-knee and hip-ankle ACC discriminated AD use, indicating that ACC may capture AD-specific control strategies. We conclude that increased variability of foot and joint displacement are indicative of motor impairment severity and may serve as therapeutic targets to restore walking after iSCI.

Keywords: AD; joint coordination; kinematics; SCI; variability; walking

Introduction

MOST INJURIES TO THE SPINAL CORD are incomplete (iSCI), resulting in partially disrupted neural circuits important for motor control and overground walking ability. Consequently, walking after iSCI is often impaired, characterized by irregular, jerky, and variable step-to-step leg movements.^{1,2} Persons with iSCI have difficulty stepping and often compensate with slower walking speeds and/or arm-driven walking aids.³ Slower walking speeds and reliance on walking aids may help overcome iSCI-induced lower extremity weakness and dyscoordination and preserve safe walking, but their impact on consistent stepping and foot placement remains unclear. Inconsistencies in stepping during overground walking may reflect underlying control deficits and compensatory strategies that compromise recovery.

Although variability in step-to-step foot placement and trajectory (i.e., kinematic variability) may be beneficial for the intact nervous system to meet demands of overground walking,⁴ studies have linked *excessive* variability to balance deficits and increased fall risk in the elderly, as well as in persons with neurological pathologies such as stroke and SCI.^{2,5,6} As a result, many clinical approaches to walking recovery are directed at reducing kinematic variability. Although reducing inconsistent stepping and foot placement are common rehabilitation therapies,⁷ the efficacy of these approaches are equivocal, because specific therapeutic targets to reduce “unwanted” variability during walking are unclear, and certain features of kinematic variability are considered important for motor learning.^{4,8} In particular, quantitative studies are needed to assess the effects of iSCI on the association between kinematic variability and overground walking ability.

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Prior studies found links between altered kinematic variability and walking performance in persons with iSCI.^{1,2,9} Although insightful, these, like many other studies, assessed variability during treadmill walking with body-weight support technologies,^{1,10,11} which do not capture the kinematic challenges of overground walking. Differences in treadmill walking and overground walking strategies have been documented,^{12,13} and results from the prior may confound the latter when identifying coordinative strategies and corresponding kinematic variability. For example, consideration is warranted for how reliance on walking aids may alter leg kinematics during overground walking. Therefore, whereas body-weight-supported treadmill walking is a useful paradigm for evaluating therapeutic approaches, identifying the relevance of kinematic variability during overground walking with and without walking aids has greater functional merit.

Kinematic variability may be linked to iSCI-induced disruption of control strategies, resulting in reduced gait speed and increased reliance on walking aids during overground walking.¹⁴ Common clinical assessments (e.g., 10 Meter Walk Test [10MWT] timed up-and-go test) are frequently used to capture walking ability after iSCI,^{9,15–18} but do not provide insight into shifts in motor control priorities during gait. Previous studies identified improved consistency in foot path (end-point) trajectories following gait training in persons with iSCI.^{1,19,20} Other studies also reported high variability in interjoint coordination (angular component of coefficient of correspondence [ACC]) in persons with iSCI.¹¹ Thus, there is converging evidence linking excessive kinematic variability with diminished walking performance, functional balance, and walking efficiency.²¹ Intriguingly, the persistence of specific types of variability, even years after injury, implies that persons with iSCI may have enough residual connections to elicit key control strategies for walking.^{1,14}

Kinematic variability during walking is often quantified as variability of footpath trajectory (end-point variability) or interjoint coordination. Both are considered indicators of walking impairment after iSCI; however, the relationship between them remains unclear. One argument is that variability in kinematics between joints may be uncoupled, with each joint contributing independently to end-point variability. End-point variability would, therefore, generally describe the degree of diminished control during foot placement. Alternatively, interjoint coordination may be employed such that end-point variability is controlled. Variability in interjoint coordination may functionally reduce end-point variability via motor redundancy from residual neural pathways after injury.²² In this case, the end-point may be controlled at the cost of increased variability and discoordination of hip, knee, and ankle joint trajectories. Identifying the relationship between variability in joint space and variability in foot trajectory may help in understanding neural strategies to preserve foot placement during overground walking in persons with iSCI. Identifying the relationships between kinematic variability (i.e., end-point, interjoint) and walking impairments also may permit more targeted rehabilitation that depends on walking aid dependency and foot placement consistency.

The purpose of this study was to quantify the effects of iSCI on leg kinematic variability during overground walking. Specifically, we characterized kinematic variability in terms of (1) foot trajectory space, using an end-point variability metric,¹ and (2) joint coordination space, using ACC.^{11,23} We further assessed the sensitivity of these spatial features to changes in cadence, overground walking speed, and walking aid type. Spinal injury is known to disrupt neural circuitry important for integrating afferent feed-

back,²⁴ which subsequently results in step-to-step delays and inaccuracies in step-to-step leg swing and foot placement during locomotion.^{2,25} Therefore, we hypothesized that persons with iSCI will show persistently high kinematic variability during overground walking as compared with able-bodied (AB) controls. Because neuromuscular deficits such as muscle weakness²⁶ and altered muscle coordination²⁷ may preclude the nervous system's ability to recruit and modulate muscles necessary for reliable step-to-step movements, we further hypothesized that deficits in leg strength (Lower Extremity Motor Score [LEMS]), walking ability (Spinal Cord Injury Functional Ambulation Inventory [SCI-FAI]), walking speed (10MWT), and reliance on walking aid (number of ground-contact points) will have a positive correlation to increased end-point and interjoint variability. Results of this study provide a comprehensive characterization of kinematic variability and the extent to which variability may contribute to walking deficits in persons with chronic iSCI.

Methods

Subjects

Sixteen persons with incomplete SCI (age, 45.7 ± 4.7 years), as defined using the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI),²⁸ and 12 age-matched controls (43.1 ± 4.4 years) participated in this study (Table 1). Healthy controls were selected to match gender, age, and approximate body anthropometry of persons with iSCI. Ethical approval for the study was received from the University's Institutional Review Board; informed consent and Health Insurance Portability and Accountability Act (HIPAA) authorization were obtained from all participants prior to their participation in accordance with the Declaration of Helsinki. We included persons who had sustained incomplete injuries to their spinal cord between levels C4 and T10, who were at least 1 year post-injury (i.e., chronic), could walk overground at least 10 m without the assistance of another person, and were able to follow simple verbal, visual, and auditory commands. We excluded participants if they had a brain injury as defined from chart review, progressive SCI, any concurrent medical condition, and/or neurological impairments.

Clinical assessments

We recorded injury severity, as well as lower extremity strength and mobility using standard clinical assessment tools. Strength was assessed using the LEMS.²⁹ The SCI-FAI was used to identify clinically observable gait deficits,³⁰ and the 10MWT³¹ to quantify maximum overground walking speed.³² Walking tests were performed using the minimum assistive device (AD) possible for safe walking.

Equipment

Leg kinematics were measured using an optical motion analysis system (Optotrak Certus; Northern Digital, Waterloo, Ontario, Canada), with nominal resolution of 0.1 mm. Two Optotrak cameras were aligned at the ends of an 8 m walkway, and captured the motion of active, infrared light-emitting position markers. Each position sensor was mounted on rigid bodies that were secured over the pelvis, thigh, shank, and heel. Conventional anatomical landmarks were defined relative to the rigid bodies, which included the hallux tip (toe), calcaneus, fifth metatarsophalangeal joint (MTP), lateral knee, medial knee, lateral malleolus, medial malleolus, greater trochanter (GT), ipsilateral anterior superior iliac spine (ASIS), contralateral ASIS, ipsilateral posterior superior iliac spine (PSIS), and contralateral PSIS.³³ Kinematic data were recorded at

TABLE 1. SUBJECT DEMOGRAPHICS

Participant	Age (yrs)	Gender	Level of injury	Years since injury	Assistive device	10MWT (m/s)	SCI-FAI	LEMS (L/R)	SS Cadence (steps/min)
1	52	M	C4	5	Walker	0.09	14	21/20	35
2	34	F	C6	1	Lofstrand	0.65	17	24/22	33
3	37	M	C8	20	None	1.28	20	25/24	110
4	39	M	T9	2	Walker	0.23	16	12/13	30
5	63	M	T3	26	Cane	0.55	14	23/23	48
6	68	M	C4	13	None	1.01	17	23/21	100
7	41	M	T8	2	Lofstrand	0.94	20	22/25	93
8	38	M	C5	8	Lofstrand	0.41	16	20/11	35
9	54	M	C7	5	Walker	NA	NA	NA	28
10	67	M	C5	1	Lofstrand	0.16	17	22/24	25
11	31	M	C8	12	Lofstrand	0.69	15	11/12	56
12	58	M	C4	40	Lofstrand	0.87	17	20/21	69
13	20	M	C4	2	None	1.00	18	16/24	74
14	30	F	T5	8	Walker	0.93	16	15/14	64
15	60	M	C6	2	None	1.42	20	25/24	68
16	39	M	T8	4	Walker	0.21	8	10/NA	32
Range	20–68		C2-T11	1–40		0.09–1.42	8–20	10–24	25–110

AIS, American Spinal Cord Injury Association Impairment Scale; SS, self-selected pace (steps/min); 10MWT, 10 meter walk test; SCI-FAI, Spinal Cord Injury Functional Ambulation Inventory; LEMS, Lower Extremity Motor Score; LS: Lofstrand crutches.

100 Hz and post-processed using custom MATLAB scripts (R2015b, The MathWorks, Inc., Natick, MA).

Protocol

To quantify the effects of iSCI on kinematic variability during overground walking, we measured end-point and interjoint variability across self-selected cadence conditions. Specifically, participants walked at three cadence conditions: self-selected cadence without auditory cue (SS), 100% of their self-selected cadence with a metronome-enabled auditory cue (SS_{met}), and 115% (F_{met}) of their self-selected cadence with a metronome-enabled auditory cue. The auditory cue was not intended for task training to reduce kinematic variability, but rather to encourage cadence matching. The order of prescribed cadence conditions (SS, SS_{met}, F_{met}) were randomized among subjects to minimize order effects. We recorded leg kinematics of the more impaired limb (defined by LEMS) while iSCI participants walked on level ground, and the same limb was recorded for their matched controls.

Prescribed cadence conditions were distinct between and within subject groups. We confirmed differences between SS_{met} and F_{met} cadence conditions for persons with iSCI (SS_{met} = 58.31 ± 26.93 steps/min, F_{met} = 67.00 ± 31.08 steps/min, $p < 0.001$) and between SS_{met} and F_{met} cadence for AB controls (SS_{met} = 110.2 ± 10.98 steps/min, F_{met} = 126.7 ± 12.75 steps/min, $p < 0.001$). As expected, persons with iSCI ($n = 16$) walked at slower SS cadences (55.53 ± 25.39 steps/min) compared with controls (110.2 ± 10.98 steps/min; $p < 0.001$). In a subset of participants with iSCI ($n = 5$), we found no difference in the mean actual walking cadence and prescribed metronome-enabled cadence cues for SS_{met} ($p = 0.71$) and F_{met} ($p = 0.56$) conditions. Cadence conditions also were highly correlated with walking speed in persons with iSCI ($p < 0.001$ for SS, SS_{met}, F_{met}) and controls ($p < 0.01$ for SS, SS_{met}, F_{met}).

Each participant performed up to 24 walking trials consisting of approximately two to five gait cycles per trial. Persons with iSCI often performed fewer trials and needed more frequent rest breaks between trials to avoid fatigue; therefore, participants were encouraged to rest as needed. A total of ~15 gait cycles were collected from each cadence condition. Trial walking speed was calculated as the mean fore-aft displacement between start and end of each experimental trial in the overground walkway. To determine maximum

walking speed (10MWT) in participants with iSCI, participants were instructed to walk as quickly and safely as possible.

Data analyses

Raw kinematic data were processed using custom code written in Matlab (Mathworks Inc., Natick, MA). We computed joint angles from kinematic trajectories of the heel, toe, MTP, GT, lateral malleolus, and lateral knee anatomical position data. Hip, knee, and ankle joint angles were calculated in accordance with International Society of Biomechanics (ISB) recommendation.³⁴

Computing gait cycles. A gait cycle was defined as the time period from ground contact of a limb (heel-strike [HS]) to subsequent ground contact of that same limb. Kinematic data were divided into gait cycles using a modified velocity-based algorithm with the PSIS marker defined as the motion reference³⁵ that translates with the participant. Heel, toe, and MTP position data were low-pass filtered using a zero-lag low-pass Butterworth fourth order filter with a 5 Hz cutoff frequency. HS events were approximated using a downward zero-crossing point of the fore-aft heel velocity. Toe-off (TO) corresponded to an upward zero-crossing point of fore-aft toe velocity. Swing phase was defined as the time between TO and HS. Range of motions at hip, knee, and ankle joints were calculated as the difference between maximum and minimum joint angle for each gait cycle, and then averaged for all trials for each cadence condition.

Quantifying end-point variability. To quantify variability of end-point foot trajectory, we computed the normalized tolerance area of fifth MTP joint, the distal-most marker of the foot, during the swing phase of gait.¹⁹ The swing phase of each cadence condition was divided into bins representing 10% increments in the horizontal excursion of each gait cycle normalized to the mean foot trajectory length (Fig. 1).^{36–38} 95% tolerance ellipses of the accumulated trajectory points were computed for each of the 10% bins. Normalized tolerance area of MTP was computed as the mean area of all ellipses. Values were reported as mean ± SD.

Quantifying interjoint coordination consistency. To quantify joint space variability, ACC¹¹ of intralimb joints was computed.

ACC provides a vector-based index of the cycle-to-cycle interjoint coordination consistency between two joints.^{23,39} A vector representing the cycle-to-cycle dispersion of hip-knee (HK), knee-ankle (KA), or hip-ankle (HA) relationships also was computed from a group of two-joint cyclograms. ACC values range from 0 to 1, where 1 indicates perfect consistency in the angular relationship between two joints across gait cycles, and a lower ACC value indicates higher joint-space variability across gait cycles. Each gait cycle was normalized to ensure same lengths of all cycles.

Statistical analysis

All statistical analyses were performed in R statistical package, Version 3.3.1.⁴⁰ Paired *t* tests were used to test the effects of cadence condition and auditory cue on end-point and interjoint coordination consistency. Two sample *t* tests were used to detect differences between AB and iSCI groups for each dependent variable (e.g., ACC). Similarly, two sample *t* tests were used to test differences in mean hip, knee, and ankle joint ranges of motion between groups for each cadence condition. Normality of the residuals were tested with quantile-quantile (Q-Q) plots and the Shapiro-Wilk test to ensure that the residuals were normally distributed about the predicted density. Nonparametric Kruskal-Wallis tests were used when the data were not normally distributed. The effect of walking aids on end-point variability and ACC was assessed using the Kruskal-Wallis test and the Tukey-Kramer post-hoc test. We quantified correlations between end-point variability and ACC measures of HK, KA, and HA using linear regression. We also quantified relationships between clinical measures (10MWT, LEMS, and SCI-FAI) and kinematic variability metrics using linear regression models. Results were considered significant at $p < 0.05$.

Results

Abnormal kinematic variability during overground walking in persons with iSCI

We found that persons with iSCI have greater kinematic variability during overground walking than do healthy controls. Con-

sistent with Grasso and coworkers, iSCI participants had higher end-point variability than controls.¹ Because cadence condition had no effect on end-point variability across AB and iSCI groups (Table 2), end-point variability measures were averaged across the three cadence conditions for each participant (Fig. 2B). End-point variability was larger in persons with iSCI (2.65 ± 1.88) than in AB (1.55 ± 0.78) ($p = 0.03$). Persons with iSCI also demonstrated greater variability in interjoint coordination for HK, KA, and HA than did controls (Fig. 3). ACCs between any combination of hip, knee, and ankle joints were lower in iSCI participants than in controls (Table 3). Consistent with Field-Fote and coworkers,¹¹ HK ACCs were lower in persons with iSCI (0.80 ± 0.11) than in controls (0.96 ± 0.02 ; $p = 0.00002$). ACC metrics for KA and HA also were lower in iSCI than in controls. Knee-ankle ACC was $\sim 19\%$ lower for participants with iSCI (0.77 ± 0.11) than for controls (0.95 ± 0.04 ; $p = 0.00003$). Similarly, HA ACC was $\sim 13\%$ lower for iSCI participants (0.79 ± 0.09) than for controls (0.91 ± 0.03 ; $p = 0.00004$). ACC for the AB group remained consistently high across all joint combinations.

There was an inverse relationship between end-point variability and interjoint coordination consistency. Low ACC was associated with high end-point variability for all three joint combinations: HK ($p = 0.0001$), KA ($p = 0.0008$), and HA ($p = 0.0006$) (Fig. 4). However, low R^2 values (0.30 and 0.34) reflect that the nature of end-point variability exhibits high variance with respect to the regression line. This implies multiple sources (e.g., altered joint coordination, reliance on walking aids) may contribute to end-point variability.

Abnormal kinematic variability indicates limited walking ability in persons with iSCI

Moderately strong linear relationships were found between ACC metrics of HK, KA, and HA and overground walking speed. ACC metrics for HK (adjusted $R^2 = 0.67$, $p = 0.00001$), KA (adjusted $R^2 = 0.59$, $p = 0.0005$), and HA (adjusted $R^2 = 0.48$, $p = 0.0026$) increased with increased 10MWT speed (Fig. 5). Similar findings were evident for ACC and trial walking speed (SS) for HK (adjusted $R^2 = 0.74$, $p < 0.00001$), KA (adjusted $R^2 = 0.63$, $p < 0.00001$) and HA (adjusted $R^2 = 0.59$, $p < 0.00001$). ACC was therefore a strong predictor of overground walking speed (Fig. 5). Although we also found that changes in end-point variability corresponded to changes in 10MWT speed (adjusted $R^2 = 0.21$, $p = 0.047$) and trial walking speed (SS) (adjusted $R^2 = 0.3$, $p = 0.002$), the relationships were weak (Fig. 5). These results suggest that high joint space variability and, to a lesser extent, end-point variability tended to be disadvantageous to fast walking. The stronger association between ACC and walking speed indicates that joint space variability was a more robust predictor of walking speed than end-point variability.

Prior studies have shown leg strength (LEMS)⁴¹ and SCI-FAI^{30,42} scores are indicators of overground walking speed. Therefore, we wished to quantify the extent to which LEMS and SCI-FAI also may relate to abnormal kinematic variability in persons with iSCI. Given prior studies focused on ACC_{HK} and that there were nonsignificant differences in ACC among HK, KA, and HA in our iSCI cohort, we focused our analyses on ACC_{HK} only. We found SCI-FAI score to be linearly related to HK ACC (adjusted $R^2 = 0.46$, $p = 0.0079$), but not end-point variability (adjusted $R^2 = 0.25$, $p = 0.067$). However, we found no relationship between LEMS score and HK ACC (adjusted $R^2 = 0.225$, $p = 0.071$) or LEMS score and end-point variability (adjusted $R^2 = 0.045$, $p = 0.47$).

FIG. 1. (A) Schematic representation of the end-point trajectory during the swing phase of overground walking. Hip, knee, and ankle joints are indicated with circles. End-point trajectory reflected the metatarsophalangeal joint (MTP) marker trajectory during the swing phase of gait. (B) Schematic depicting the computation of normalized tolerance area of MTP marker trajectory; 95% tolerance ellipses of accumulated trajectory points computed for each bin of the swing phase normalized to the mean foot trajectory length, MTP, fifth metatarsophalangeal joint; AB, able-bodied; SCI, spinal cord injury; EV, end-point variability.

TABLE 2. iSCI SUBJECTS HAD HIGHER END-POINT VARIABILITY THAN THE AB GROUP UNDER ALL CADENCE CONDITIONS

Group	End-point variability			
	All (SS_{met} F_{met} SS)	SS_{met}	F_{met}	SS
iSCI ($n = 16$)	2.65 ± 1.88	2.48 ± 1.63	2.50 ± 2.00	2.98 ± 2.08
AB ($n = 12$)	1.55 ± 0.78	1.52 ± 0.77	1.87 ± 0.94	1.29 ± 0.54

AB, able-bodied cohort (controls); SS, self-selected walking cadence, no metronome; SS_{met} , self-selected walking cadence of incomplete spinal cord injury (iSCI) group with metronome feedback; F_{met} , fast walking (115% of SS_{met}) cadence of iSCI group with metronome feedback.

Walking aids impact interjoint variability and walking speed in persons with iSCI

Reliance on walking aids (number of contact points) corresponded to ACC, but not to end-point variability. We found that ACC decreased with increased number of ground contact points of the AD (i.e., No AD:0, Cane:1, LS:2, Walker:4). HK ACC values were 0.88 ± 0.02 for the No AD group, 0.84 ± 0.07 for the LS/Cane group, and 0.69 ± 0.10 for the Walker group. There was a significant difference in ACC_{HK} among three groups ($H[2] = 8.17$, $p = 0.02$). Post-hoc comparison revealed that ACC_{HK} of the Walker group was significantly different from that of the No AD group (Tukey–Kramer test; $p = 0.01$). ACC_{KA} values were 0.84 ± 0.01 for the No AD group, 0.81 ± 0.08 for the LS/Cane group, and 0.66 ± 0.12 for the Walker group. No significant differences were

found among groups ($H[2] = 5.03$, $p = 0.08$). ACC_{HA} values were 0.83 ± 0.02 for the No AD group, 0.83 ± 0.05 for the LS/Cane group, and 0.69 ± 0.08 for the Walker group. There was a significant difference in ACC_{HA} among three groups ($H[2] = 6.64$, $p = 0.036$) but no significant differences in the pairwise comparison. However, we found that reliance on walking aids did not contribute to greater end-point variability. End-point variability was not different between the Walker and LS/Cane groups (Tukey–Kramer test; $p = 0.99$), Walker and No AD groups (Tukey–Kramer test; $p = 0.10$), and LS/Cane and No AD groups (Tukey–Kramer test; $p = 0.09$) (Fig. 6).

Reliance on walking aids corresponded to reduced walking speed. During the 10MWT, average values were 1.17 ± 0.21 m/sec for the No AD group, 0.61 ± 0.27 m/sec for the Cane/LS group, and 0.37 ± 0.38 m/s for the Walker group. There was a significant difference in 10MWT among the three groups ($H[2] = 8.95$, $p = 0.01$). We found that the No AD group walked significantly faster than the Walker group (Tukey–Kramer test; $p = 0.01$) and the LS/Cane group (Tukey–Kramer test; $p < 0.05$).

Increased cadence and auditory cues did not influence kinematic variability

We quantified the extent to which cadence and auditory cues may affect kinematic variability estimates in iSCI and control subjects. First, we found metronome-enabled auditory cuing had no effect on end-point variability (SS vs. SS_{met} , paired t test) in persons with iSCI ($p = 0.21$) and healthy controls ($p = 0.34$). Similarly, cadence condition (SS_{met} and F_{met} , paired t test) did not alter end-point variability for iSCI persons ($p = 0.97$) or controls ($p = 0.84$). Second, metronome-enabled auditory cues did not impact interjoint coordination consistency (ACC) among hip, knee, and ankle for either iSCI group (HK, $p = 0.95$; KA, $p = 0.67$; HA, $p = 0.84$) or AB group (HK, $p = 0.26$; KA, $p = 0.47$; HA, $p = 0.44$). Lastly, cadence had no effect on ACC estimates in the iSCI group (HK, $p = 0.55$; KA, $p = 0.77$; HA, $p = 0.27$) and limited effect on ACC estimates in the AB group (HK, $p = 0.45$; KA, $p = 0.98$; HA, $p = 0.05$). Collectively, these results indicate that cadence and auditory cue did not influence our estimates of kinematic variability in persons with iSCI and healthy controls.

As expected, faster walking cadence contributes to faster walking speed, as well as to increased joint range of motion in the iSCI and control groups. Fast cadence using an auditory cue increased walking speed in controls (SS_{met} vs. F_{met} , $p = 0.00006$) and participants with iSCI (SS_{met} vs. F_{met} , $p = 0.0009$). Hip range of motion also increased by faster cadence in controls (SS_{met} vs. F_{met} , $p = 0.005$) and persons with iSCI (SS_{met} vs. F_{met} , $p = 0.03$). However, knee ($p = 0.74$) and ankle ranges of motion ($p = 0.10$) were not found to differ across cadence conditions in persons with iSCI.

Persons with iSCI had an altered joint range of motion during self-selected walking as compared with controls (Fig. 7). Knee joint

FIG. 2. (A) End-point foot trajectory during the swing phase in one representative control subject compared with one incomplete spinal cord injury (iSCI) subject. See Methods. X-axis: fore-aft position; zero indicates the reference point (posterior superior iliac spine [PSIS]) in the sagittal plane. Y-axis: vertical elevation in sagittal plane. (B) Comparison of end-point variability during the swing phase for able-bodied (AB) and iSCI groups. Each data point represents the mean end-point variability for each subject averaged across cadence conditions. Lower values for end-point variability indicate less variability. Mean and standard deviation of each condition are listed in Table 2 (column “All”). Bold dots indicate outliers. AB, able-bodied cohort (controls). AB subjects walked without an assistive device. SCI, subjects with spinal cord injury.

FIG. 3. *Left.* Representative joint-space traces (cyclograms) from an able-bodied (AB) control and a person with incomplete spinal cord injury (iSCI). Angular coefficient of correspondence (ACC) values for each indicated in the lower right corner. *Right.* Interjoint coordination consistency (ACC) between hip-knee (HK), knee-ankle (KA), and hip-ankle (HA). An ACC value of 1 indicates perfect consistency of interjoint coordination for two joints across multiple gait cycles. In all three joint combinations, iSCI had significantly lower ACCs than AB. Bold dots indicate outliers.

range of motion was significantly reduced in iSCI as compared with controls ($p < 0.0001$). We also observed between-group differences in ankle and hip range of motion, but because of large within-group variances, the means were not found to differ from controls for the ankle ($p = 0.62$) and hip ($p = 0.053$). Despite limited joint range of motion, iSCI demonstrated greater interjoint and end-point variability during overground walking than controls.

Discussion

Converging evidence shows that excessive kinematic variability is linked with diminished walking ability in persons with chronic iSCI. In this study, we found that iSCI participants had increased variability of foot trajectory (end-point) and reduced interjoint coordination (ACC), which were invariant to changes in walking. We also found that more impaired persons with iSCI who presented with deficits in overground walking and greater reliance on walking aids had the greatest variability. This study provided a comprehensive characterization of both end-point and interjoint variability and the extent to which they may contribute to underlying constraints on overground walking in persons with chronic iSCI. To clarify the contribution of compensatory mechanics to variability inherent during community ambulation, we further characterized the sensitivity of kinematic variability to AD use during overground walking.

Consistent with our hypothesis, we found that persons with iSCI have greater kinematic variability than AB individuals. Variability at both end-point and joint space (ACC) was observed in persons with iSCI, which strongly predicted walking speed. This result confirmed prior evidence that lower limb kinematic variability provides a complementary readout of functional recovery.^{11,39} However, whereas ACC and end-point variability remained persistently high across walking cadences, only joint space variability dissociated the type of AD used. Together, these observations indicate that interjoint coordination uniquely captures motor strategies specific to AD type, whereas end-point variability more coarsely reflects altered walking mechanics. Complementary assessments of gait variability may therefore provide important measures of walking recovery, AD-specific mechanics, and further refine targeted rehabilitative strategies.

End-point variability increased after iSCI

End-point variability during overground walking was increased in persons with iSCI as compared with controls. However, estimates reported in this study were smaller than those previously reported for treadmill walking in controls¹ and persons with iSCI.¹¹ This difference may be partly explained by differences in injury severity, as Grasso analyzed more impaired patients, including American Spinal Injury Association (ASIA) A and B classification. The lower end-point variability may additionally reflect differences between walking overground with AD and body-weight-supported treadmill walking. Some may argue that body-weight-supported treadmill walking used in previous studies^{1,43,44} affords a more controlled experimental setup. However, this does not necessarily reflect the biomechanical demands of community ambulation. Most of our participants use AD daily to enable mobility and to ensure safety while performing daily living activities. Use of different AD types may introduce unique constraints on end-point variability, which cannot be captured during body-weight-supported treadmill walking. For example, we found that persons using walkers had similar end-point variability to that of users of other walking aids despite demonstrating significantly slower walking speeds and

TABLE 3. MEAN ACC FOR HIP-KNEE (HK), KNEE-ANKLE (KA), AND HIP-ANKLE (HA) FOR iSCI AND AB GROUPS

Group	ACC (HK)			
	All	SS _{met}	F _{met}	SS
iSCI	0.80 ± 0.11	0.80 ± 0.12	0.81 ± 0.11	0.79 ± 0.10
AB	0.96 ± 0.02	0.97 ± 0.01	0.97 ± 0.01	0.95 ± 0.04
	ACC (KA)			
	All	SS _{met}	F _{met}	SS
iSCI	0.77 ± 0.11	0.77 ± 0.12	0.78 ± 0.11	0.76 ± 0.12
AB	0.95 ± 0.04	0.95 ± 0.02	0.95 ± 0.02	0.93 ± 0.06
	ACC (HA)			
	All	SS _{met}	F _{met}	SS
iSCI	0.79 ± 0.09	0.79 ± 0.09	0.80 ± 0.09	0.78 ± 0.09
AB	0.91 ± 0.03	0.91 ± 0.03	0.93 ± 0.03	0.90 ± 0.05

ACC, angular coefficient of correspondence; AB, able-bodied cohort (controls); SS, self-selected walking cadence, no metronome; SS_{met}, self-selected walking cadence of incomplete spinal cord injury (iSCI) group with metronome feedback; F_{met}, fast walking (115% of SS_{met}) cadence of iSCI group with metronome feedback.

lower ACCs. Therefore, end-point variability likely encompasses kinematic features of AD use that are relevant to daily living for those with iSCI during overground walking.

Interjoint coordination consistency (ACC)

Persons with iSCI had significantly lower ACC_{HK}, ACC_{KA}, and ACC_{HA} than AB, confirming our prediction of iSCI-induced inconsistencies in interjoint coordination. Computed ACC_{HK} values in the present study are similar to the findings of Field-Fote and coworkers,¹¹ in which a range of 0.4–0.8 was reported for iSCI participants before gait training. However, we reported greater ACC_{HK} range (0.62–0.95) for our iSCI participants. Higher ACC values may be attributed to key methodological differences such as overground walking in the absence of body-weight support, and the use of AD. The higher coordination consistency during overground walking may indicate that participants employed familiar, everyday gait strategies while using their ADs and did not have to make additional kinematic adjustments to account for unfamiliar support from a body-weight-support harness. The greatest reduction in intralimb coordination was observed between the knee and ankle (ACC_{KA}) in our iSCI participants, possibly resulting from specific sensorimotor deficits that differentially effect distal joints such as

spasticity⁴⁵ and supraspinal drive.⁴⁶ The nonsignificant difference in the hip range of motion between groups may further indicate that the hip joint contributes least to the degradation of coordination consistency. Whereas the observed variability in the range of motion for the hip and ankle joint appears large, excessive plantar flexion and hip flexion have been reported in the literature.⁴⁷

ACC uniquely distinguishes between the types of AD used

Although end-point variability and ACC were effective in predicting walking speed, only ACC distinguished between types of AD used. In particular, we found that participants who used walkers exhibited lower ACC values than users of less restrictive devices (Fig. 6). Users of walkers demonstrated an atypical relationship among end-point variability, ACC, and walking speed; those subjects maintained end-point variability, but walked more slowly with lower ACC. Walkers appeared to constrain foot placement but not interjoint coordination. Therefore, the lower ACC values could also be explained by alternative coordinative strategies exclusively used by participants who use walkers or by those with the greatest gait impairments. In general, ACC was lower in those participants using more supportive AD (greater number of contact points), suggesting

FIG. 4. End-point variability versus angular coefficient of correspondence (ACC) across three joint combinations: hip-knee (HK), knee-ankle (KA), and hip-ankle (HA). Line indicates linear regression and gray shaded region delineates 95% confidence interval. Each marker represents one subject, and subjects are shape-coded by type of assistive device. In all three joint combinations of ACC, the relationship between end-point variability and ACC was significant, as indicated by the *p* values.

FIG. 5. Relationship between walking speed and variability. **(A)** End-point variability and angular coefficient of correspondence (ACC) versus walking speed from the 10 Meter Walk Test (10MWT). **(B)** End-point variability and ACC versus trial walking speed during overground walking (self-selected cadence). Only hip-knee ACC is shown. The relationship between end-point variability and walking speed as well as the relationship between ACC and walking speed were significant. Line indicates linear regression and gray shaded region delineates 95% confidence interval. Shaded ellipse indicates 95% confidence ellipse for able-bodied (AB) data. For the first column, trial walking speed was used for AB ellipses, because the 10MWT was not performed with AB controls. Therefore, for AB data, the ellipses in the left and right columns are equivalent and positioned at the same coordinates for comparison with the data from those with incomplete spinal cord injury (iSCI). Each marker represents one subject and is shape-coded by types of assistive device.

that greater interjoint variability may necessitate greater assistance for walking and/or stability. We suspect that end-point variability alone may be too coarse a metric to capture discriminating features of walking performance across AD use.

Cadence and auditory cueing do not affect spatial variability parameters

A rhythmic auditory cue in walking has been used in many patient groups to reduce temporal variability in stride and swing time⁴⁸ and to adjust temporal parameters such as cadence in iSCI.⁴⁹ However, the effect of metronome-enabled auditory cues on spatial end-point kinematic variability in iSCI has not been investigated until now. Our results showed that the addition of auditory cue via metronome (SS vs. SS_{met}) changed neither interjoint coordination consistency nor end-point variability. This suggests that a temporal auditory cue, although influencing the temporal variability (e.g., step time), does not necessarily affect the variability of spatial

parameters (end-point variability and ACC) during overground locomotion. The lack of modulation in end-point variability and ACC with cadence (SS_{met} vs. F_{met}) indicates that AB and iSCI participants did not alter their spatial coordination strategies to achieve faster cadence.

Possible sources of variability: compensation and neural recovery

The significant deviations of lower limb gait parameters after iSCI² are a result of reduced descending input to spinal sensorimotor circuitry involving adaptive and maladaptive plasticity along the neural axis.⁵⁰ Kinematic variability therefore reflects the cumulative effect of neural recovery and/or compensatory strategies that may undermine walking recovery. Although our study cannot discern the relative contribution of these two sources of variability, the current findings provide a step toward understanding variability as a downstream marker of functional recovery. This is supported by the

FIG. 6. Impact of types of assistive devices (AD) on end-point variability, angular coefficient of correspondence hip to knee (ACC_{HK}) and the 10 Meter Walk Test (10MWT) speed in persons with incomplete spinal cord injury (iSCI). Ranges of ACC and speed are separated by the level of AD support. When divided into three groups according to the number of ground contacts per device (e.g., Cane: 1, LS:2, Walker:4), ACC and speed both decreased as the number of ground contacts per device decreases, whereas there was no difference among groups in end-point variability. Note that cane and LS are grouped together because there was only one cane user and the numbers of ground contacts per device were similar.

finding that both measures of variability were related to a highly regarded clinical measure of gait performance, the 10MWT. Furthermore, end-point variability was inversely related to ACC, suggesting that the inability to reliably control joint coordination in

persons with iSCI leads to high variability in foot trajectory. Together this evidence suggests a compelling link between high variability in coordination and in foot trajectory predict motor performance. It remains to be seen if specific types of gait variability provide further insight into an individual's capacity for functional recovery, which targeted rehabilitation strategies may leverage.

The ability of gait performance metrics to reflect the more specific concept of neural recovery, a form of adaptive plasticity on the neural axis, remains debated in the literature. Recently, Awai and colleagues published evidence supporting the idea that measures of interjoint coordination are more related to changes in neural recovery level than clinical measures of gait performance (walking speed, step length). They reported that persons with iSCI were unable to modulate cyclogram configuration with increased walking speed²³ and rehabilitation,³⁹ whereas ACC increased during rehabilitation.¹⁹ However, other studies of locomotor patterns in iSCI described the normalization of end-point variability after treadmill training without parallel restitution of muscle activation patterns.²⁰ The ability to normalize end-point and joint space variability but not cyclogram configuration may suggest the development of compensatory movement strategies, rather than neural restoration. Inconsistencies in the observed ACC values across AD types (Fig. 6) may further indicate that the absence of normal motor patterns does not necessarily indicate the lack of motor recovery alone, but rather AD-specific biomechanical compensations. Longitudinal studies that track training-induced plasticity may provide a better paradigm to determine if kinematic variability during walking can function as a suitable marker of neural recovery.

Limitations

Our study was limited to a convenience sample of 16 persons with iSCI, with heterogeneity in each individual participant's time since injury, level of injury, and functional capability. The range of variability across the iSCI participants attests to the fact that even among persons with well-recovered ambulatory strategies, individual differences are important. Additionally, the nonsignificant effect of cadence condition on the variability metrics may only

FIG. 7. Joint ranges of motion of knee, ankle, and hip for able-bodied (AB) and incomplete spinal cord injury (iSCI) groups during overground walking at a self-selected speed.

reflect the limited range of the two cadence conditions tested, namely SS_{met} and F_{met} . Further, the varying capabilities of the persons with iSCI are further confounded by the type of assistive device used.^{51,52} Given that specific ADs induce varying degrees of biomechanical constraints on the participant,⁵³ the current findings provide a strong case against collapsing iSCI participants into a single group across AD type. Participants who use different ADs may have adopted alternative walking mechanics,⁵³ which are differentially reflected across each gait variability metric (i.e., ACC for walker AD). The generally slower walking speed of those who use walkers confounds the ability to discern the pure effect of AD type on variability from speed or impairment level.⁵² Crucially, the degree to which iSCI participants relied on the AD was not explicitly tested here and requires appropriate assessments of upper limb AD reliance,⁵⁴ such as force transmitted through the AD. Overall, the variability in coordination across ADs highlights the need for future studies to more explicitly delineate the effect of AD on clinical assessments of gait performance and impairment level.

Clinical implications: Preserving adaptive variability

This study reinforces the notion that interjoint coordination makes an important contribution to many different aspects of gait, including speed and step-to-step foot placement. Additionally, the current findings qualify the importance of considering the AD used,^{51,54} rather than looking for a one-therapy-fits-all gait rehabilitation strategy. The question arises as to whether different types of gait variability serve an adaptive, functional significance. Perhaps persons with iSCI adaptively use variability in coordination to facilitate motor equivalent goals,²² such as footpath trajectory.^{1,14} Rehabilitation strategies prioritizing the restoration of a normative pattern of interjoint covariation may counterproductively remove this adaptive variability and negatively impact functional recovery. Whether reducing foot path variability leads to faster walking speed remains inconclusive, especially when considering AD reliance.⁵² Further, the finding that LEMS did not correlate with either type of kinematic variability suggests that residual joint strength may not be as consequential to gait recovery as utilizing a compensatory strategy. On the other hand, the significant correlation of the SCI-FAI score and ACC affirms the idea that broader assessments of multi-joint coordination may be functionally more informative than single joint deficits.¹¹ Nevertheless, kinematic variability may be a relevant marker of gait impairment,⁵⁵ representing the cumulative effects of neural plasticity and compensatory neuromechanics. Optimal joint control post-injury may be better recast in terms of accommodating and identifying functional variability,¹⁴ in opposition to achieving kinematic restitution. Although various treatment paradigms such as treadmill training,^{1,10} low oxygen therapy,⁵⁶ and intensive gait rehabilitation⁵⁷ have resulted in improved walking performance, their impact on kinematic variability remains unclear. Indeed, questions remain as to whether the benefits of these treatment approaches may be, in part, the result of reduced abnormal kinematic variability.

Conclusion

A comprehensive assessment of kinematic variability during overground walking in persons with iSCI revealed an inverse association between end-point variability and interjoint coordination consistency. Both robustly predicted gait performance across different walking conditions. However, despite the consistently lower end-point variability in persons with iSCI, the sensitivity of variability in joint space to discriminate AD type indicates that specific types of gait variability may more directly reflect functional strat-

egies used for community ambulation. Therefore, whereas the present study affirms a compelling link between lower limb variability and motor impairment, types of gait variability differentially capture the cumulative effect of both adaptive neural recovery and compensatory motor strategies that are not easily disassociated. Additional studies are needed to better quantify how plasticity-promoting treatment approaches may modify or guide these compensatory motor strategies and subsequently enhance recovery of walking after iSCI.

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