Meaningful Measurements of Maneuvers: People With Incomplete Spinal Cord Injury ‘step Up’ to the Challenges of Altered Stability Requirements

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Research

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Abstract

Background: Many people with incomplete spinal cord injury (iSCI) have the ability to maneuver while walking. However, neuromuscular impairments create challenges to maintain stability. How people with iSCI maintain stability during walking maneuvers is poorly understood. Thus, this study compares maneuver performance in varying external conditions between persons with and without iSCI to better understand maneuver stabilization strategies in people with iSCI.

Methods: Participants with and without iSCI walked on a wide treadmill and were prompted to perform lateral maneuvers between bouts of straight walking. Lateral force fields applied to the participants’ center of mass amplified or damped the participants’ movements, thereby increasing the bandwidth of the study to capture behavior at varied levels of challenge to stability.

Results: By examining metrics of stability, step width, and center of mass dynamics, distinct strategies emerged following iSCI. The minimum margin of stability ($MOS_{\text{min}}$) on each step during maneuvers indicated persons with iSCI generally adapted to amplified and damped force fields with increased stability compared to persons without iSCI, particularly using increased step width and reduced center of mass excursion on maneuver initiation. In the amplified field, however, persons with iSCI had a reduced $MOS_{\text{min}}$ when terminating a maneuver, likely due to the challenge of the force field opposing the necessary lateral braking. Persons without iSCI were more likely to rely on or oppose the force field when appropriate for movement execution. Compared to persons with iSCI, they reduced their $MOS_{\text{min}}$ to initiate maneuvers in the damped and amplified fields and increased their $MOS_{\text{min}}$ to arrest maneuvers in the amplified field.

Conclusions: The different force fields were successful in unpacking relatively subtle strategy differences between persons with and without iSCI. Specifically, persons with iSCI adopted increased step width and reduction in center of mass excursion to increase maneuver stability in the amplified field. The amplified field may provoke practice of stable and efficient initiation and arrest of walking maneuvers. Overall, this work allows better framing of the stability mechanisms used following iSCI to perform walking maneuvers.

1. Background

It is difficult to resolve the strategies people use to skillfully stabilize their bodies during walking maneuvers. Stability, the tendency for a system to return to a consistent state, is generally considered beneficial during straight walking. However, it has been difficult to quantify stability during maneuvers given that the objective of a maneuver is to safely breach the current state and transition to an alternative stable state (e.g. straight walking in a path parallel but lateral to the previous one). Maneuvering, an essential skill for community ambulation, can be accomplished with varying strategies of foot placement, body movements, and ground-on-foot force control (1). However, our understanding of how people adapt stepping strategies to manage stability during maneuvers is poor.
The need to understand these stabilizing strategies among people who have sustained a motor-incomplete spinal cord injury (iSCI) is particularly pressing. iSCI disrupts balance and challenges one's ability to safely and efficiently perform maneuvers. In addition, iSCI often limits strength and coordination, which may restrict the options for stabilization strategies. Difficulty maneuvering is likely a contributing factor to the reduced mobility (2) and high fall rate (3) observed among ambulatory individuals with iSCI. A greater understanding of how people manage stability during walking maneuvers could provide valuable insight for designing more effective interventions to enhance the ability to maneuver after iSCI.

To better understand how people perform lateral 'lane change' maneuvers during forward walking (4) (Fig. 1), velocity-dependent force fields can be applied in either the same (amplifying) or opposite (damping) direction as the lateral center of mass (COM) velocity. Maneuvering requires a lateral velocity-time profile of the COM that is different from straight walking, including a prolonged period of COM excursion in the direction of the maneuver and the subsequent arrest of that motion. Thus, lateral velocity-dependent force fields allow for richer characterization of the maneuver by altering the physical requirements for breaching and then reestablishing forward walking stability. Damping lateral COM velocity will increase frontal-plane stability during forward walking, which should resist the transition into a lateral maneuver but assist the arrest of the maneuver. Vice versa, amplifying lateral COM velocity will decrease frontal-plane stability during forward walking (5), which should assist the transition into a lateral maneuver but increase the challenge to arrest the maneuver. The current study introduces both Damped and Amplified fields to a lateral maneuver task to evaluate how different stability requirements affect the strategies people with and without iSCI use to maneuver.

Similar damping (6) and amplifying (5, 6) force fields have been valuable for understanding stability-related consequences of the stepping strategies adopted during straight walking. People with and without iSCI tend to modify lateral margins of stability (MOS), the distance between a velocity-adjusted COM position and the edge of an individual's base of support (BOS), in response to changes made by external viscous force fields. By increasing or decreasing lateral MOS, the impulse needed to cause frontal plane instability (based on an inverted pendulum model of walking (7)) can be changed in accord with the challenges of a task. Thus, the adaptive stepping strategies and associated changes in lateral MOS used to first breach and then reestablish forward walking stability for a lateral maneuver are expected to manifest on steps initiating, executing, and terminating lateral maneuvers (Fig. 1) in the presence of force fields that damp and amplify lateral COM velocity.

To address gaps in understanding the stability and stepping during maneuvers, this study characterized strategies used by people with and without iSCI performing lateral "lane-change" maneuvers during forward walking in Damped, Amplified, and Null force fields. As observed in previous studies of straight walking (6), it was expected that participants with iSCI would maintain a larger MOS across fields in comparison to their peers without iSCI. Considering findings of maneuvering without force fields (1, 8) the MOS was expected to be smallest on the initiation step (Fig. 1) as participants bias their COM in the maneuver direction in anticipation of the impending movement and largest on the execution step as
individuals generate a lateral impulse by pushing off of the limb contralateral to the maneuver direction. Given the adaptability of stepping behavior in previous work (5, 9), it was expected that people would adapt their stepping strategy to use the fields to aid their maneuvers when advantageous. The Damped field may be advantageous during the maneuver termination, while the Amplified field may be advantageous during the maneuver initiation/execution.

In the Damping field, we hypothesized that relative to the Null field, participants would 1) decrease the minimum lateral MOS (MOS$_{\text{min}}$) on the initiation step (Fig. 1) to facilitate the maneuver by biasing COM position towards the maneuver direction, 2) increase MOS$_{\text{min}}$ on the execution step to increase potential for lateral ground-on-foot force in the direction of the maneuver to counter the opposing field, and 3) decrease MOS$_{\text{min}}$ on the termination step to take advantage of the field reducing the need to brake. In the Amplified field, we hypothesized that relative to the Null field, participants would 1) increase MOS$_{\text{min}}$ ipsilateral to the maneuver direction on the initiation step to afford increased stability, anticipating the assistance of the force field to overcome that stability on the subsequent execution step 2) decrease the MOS$_{\text{min}}$ contralateral to the maneuver on the execution step to leverage assistance from the force field and 3) increase the lateral MOS$_{\text{min}}$ ipsilateral to the maneuver direction on the termination step to prevent overshoot of the target end-position. We expected the termination step MOS$_{\text{min}}$ increase to be especially evident in individuals with iSCI given their intensified cautious response to destabilizing fields in previous work (6). Step width, COM excursion, and COM peak velocity were also quantified to further unpack the strategies contributing to differences in MOS$_{\text{min}}$.

2. Methods

2.1 Participants

Twenty-four people provided informed consent and participated in the study. Northwestern University and Edward Hines Jr. VA Hospital Institutional Review Boards approved the study protocol. Participants (Table 1) included 12 adults with iSCI (injury level ranging from C3 to T9) and 12 age- (±5 years) and gender-matched individuals with no documented neurological or balance impairments (iSCI age 48 ± 15 years, non-iSCI age 47 ± 15 years, 4 females in each group). Inclusion criteria included: spinal cord injury level between C1-T10, American Spinal Injury Association Impairment Scale (AIS) C or D, >6 months since initial injury, range of motion within functional limits of ambulation, ability to walk 10 m without assistive devices or physical assistance, no excessive lower limb spasticity of the quadriceps or hamstring muscle groups as measured by a score of >3 on the Modified Ashworth Scale, and ability to tolerate 10 minutes of standing. Exclusion criteria included severe cardiovascular or pulmonary disease, recurrent fracture history, known lower extremity orthopedic problems, concomitant central or peripheral neurologic injury, and inability to provide informed consent due to cognitive impairments.

2.2 Experimental Setup
Participants walked on an oversized treadmill (belt width 1.39 m; Tuff Tread, Willis, TX) that provided room to safely perform lateral walking maneuvers. Participants wore a trunk harness attached to an overhead anchor (ZeroG Passive, Aretech). The harness provided no support during walking but could catch the participant in the case of a fall. Attachment of the harness to the overhead anchor was adjusted for each participant so their ability to perform lateral maneuvers was not restricted. Participants did not use handrails, or assistive devices during trials. As an additional safety precaution, spotters provided non-contact guard to participants with iSCI during treadmill walking.

Participants received visual feedback about their lateral position on the treadmill from a projection of a line representing the lateral position of the COM (estimated in real time as the midpoint of greater trochanter motion capture markers) and a target “lane” (Fig. 1, 0.25 m wide) on the treadmill belt. The lane was offset to the left or right half of the treadmill, depending on the intended maneuver direction. Participants walked at their preferred treadmill speed (iSCI 0.60 ± 0.2 m/s, non-iSCI 1.0 ± 0.2 m/s) and were instructed to do their best to keep their COM line within the lane. To cue maneuvers, the lane projection location on the treadmill was instantaneously moved to the opposite side (right or left) of the treadmill. The distance between lane centers of the prior and new target lanes was 30 cm.

Participants were instructed to maneuver as safely and efficiently as possible to the new lane location. Once the participant's COM entered the new target lane, a predetermined number of steps was required before another target lane switch. To reduce the possibility that participants would predict the timing of the target lane switch, the number of steps (3–8 steps) occurring between maneuvers was randomized every maneuver and unknown to the participant. The target lane switch always occurred ~ 100 ms after a heel strike of the foot contralateral to the maneuver direction (i.e. right heel strike when the lane was to switch from the right to left side of the treadmill, and vice versa).

Participants performed the walking maneuvers in three lateral force field conditions: Damped, Amplified and Null. Participants wore a harness around their hips that was snug but allowed for typical limb motion. This harness attached to the cables of the Agility Trainer robotic device (10), which applied lateral forces to the pelvis in two of three experimental conditions (Damped and Amplified). During these conditions, the applied lateral force was proportional in magnitude to the person's real-time lateral COM velocity. In the Damped and Amplified conditions, the force was in the opposite and same direction as lateral COM velocity, respectively. These fields used a viscous gain of ± 40 Ns/m in their respective directions, similar in magnitude to fields used in previous studies (5, 11). Forces were also capped at 80N for all participants for safety. During the Null condition, the cables were not attached to the harness and thus exerted no force on the participant. The order of the conditions was randomized for each participant.

A 12-camera motion capture system (Qualisys AB, Gothenburg, Sweden) recorded 3D marker locations at 100 Hz. Thirteen active-LED motion capture markers (3 markers on pelvis, bilaterally on the greater trochanters, lateral malleoli, calcanei, and second and fifth metatarsals) were used to capture lower-limb kinematics. Force sensing resistors were attached to the bottom of each foot to detect steps in real time with signal transmission via the Delsys Trigno wireless acquisition system (Delsys, Natick, MA).
2.3 Protocol

Demographic measure collection and clinical assessments of strength and walking function were performed by a licensed physical therapist before the experimental protocol. Clinical tests for participants with iSCI included the lower extremity motor score (LEMS) portion of the American Spinal Injury Association Impairment Scale (AIS), the 10 Meter Walk Test (10MWT (12–14)) performed at each participant’s preferred and fast speeds, the functional gait assessment (FGA) (15), and walking index for spinal cord injury (WISCI II) (16, 17). Individuals without iSCI performed the FGA and 10MWT. For treadmill walking, participants’ preferred speeds were assessed by iterating changes in treadmill speed until the participants reported their preference (~ 2 min walking). Preferred speed was determined when walking with no external assistance. For the main experiment, participants performed trials in 3 force field conditions (Null, Damped, and Amplified). The order of the 3 force field conditions was randomized for each participant, and all walking was performed at an individual’s preferred speed. During each condition, participants performed the following in order:

1. **Maneuver Practice in the Force Fields - Treadmill Off** - Participants performed four lateral maneuvers with the field on and treadmill speed set to zero to gain an initial sense of the task in the field.

2. **Maneuver Practice in the Force Fields - Treadmill On** - Participants performed one minute of straight walking with the field on and the treadmill moving at the participants preferred speed immediately followed by four lateral walking maneuvers with the treadmill on to further familiarize the participant with the task in the field.

3. **Rest** – 30 s standing rest.

4. **Maneuver Task in the Force Fields with the Treadmill On** - Participants performed eight walking maneuvers in the field with the treadmill moving at their preferred walking speed. Data from this task was used for analysis.

2.4 Processing & Analysis

Kinematic marker data was processed using Visual3D (C-Motion, Inc., Germantown, MD). Marker data was gap-filled (3rd order polynomial with maximum gap of 10 frames) and low-pass filtered (Butterworth, 6 Hz cut-off frequency). Mediolateral COM position and velocity were calculated in Visual3D using the built-in “Visual3D pelvis” model and pelvis marker data.

Step metrics were calculated using a custom LabVIEW (National Instruments, Austin, TX) routine. Lateral MOS<sub>min</sub> (7) during stance period (heel strike to toe-off) was used to assess stability during the maneuver initiation, execution, and termination steps (Fig. 1). MOS was calculated during the stance phase of each foot using the lateral malleoli as the edge of the BOS, and the MOS<sub>min</sub> identified as the smallest MOS occurring within each step. Step width, COM excursion, and COM peak velocity were also calculated. Step width was calculated as the lateral distance between calcaneus markers at heel strike of the steps.
assessed for MOS_{min}. COM excursion was the lateral distance between the furthest left and right excursions of the COM during stance and peak velocity was the largest lateral speed of the COM toward the stance foot in that period.

To assess differences in MOS_{min}, step width, COM excursion, and peak lateral COM velocity for the three maneuver steps between groups and fields, a linear mixed-effects model was fit for each metric using maximum likelihood estimations in SPSS (IBM). The models specified fixed effects for step (initiation, execution, and termination) and the interaction between step, group (iSCI and without iSCI), and field (Damped, Amplified, and Null) with random intercepts for participants. Each maneuver was treated as a single observation, totaling 8 observations per step per field per person. Linear contrasts with Bonferroni corrections were used to evaluate the significance of differences in each dependent variable between groups and fields within the three steps.

3. Results

3.1 Participants & General Protocol

Participants with and without iSCI were able to perform the maneuver task in all three fields. One participant with iSCI was excluded in final statistical analysis due to missing motion capture data. Metrics by participant are shown in Table 1.

Across conditions and groups, participants typically followed the pattern of stepping shown in Fig. 1. That is, participants waited almost a full gait cycle after the target lane changed location during midstance of a step on the foot contralateral to the maneuver direction to begin movement into the new lane (execution step, Fig. 1). Participants had their COM in the target lane by heel strike of the step following the “termination step” (Fig. 1). For most maneuvers (80.8%), there were no intermediate steps between the execution and termination steps, as illustrated in Fig. 1. A few maneuvers within both groups, particularly in the Damped field, had one (17.9%) or at most two (1.2%) intermediate steps on the foot contralateral to the maneuver direction before the COM was in the target lane. The COM path and MOS of an example maneuver are also shown in Fig. 1.

3.2 Margin of Stability Between Groups & Steps

MOS_{min} was significantly different between the initiation, execution, and termination steps and consistent with expectations that MOS_{min} would be smallest on the initiation step (p = 0.000 compared to execution and termination) and largest on the execution step (p = 0.000 compared to initiation and termination). Figure 2 shows mean trends across steps within groups and fields. Figures 3–5 show the distribution of MOS_{min} measurements across conditions and groups, and significant interactions between groups and fields within steps.

3.3 Initiation Step
On the initiation step (Fig. 3), participants with iSCI had a significantly larger MOS$_{\text{min}}$ than those without iSCI in both the Damped (p = 0.003) and Amplified (p = 0.006) force fields. This occurred with individuals with iSCI exhibiting significantly larger step widths in the Damped and Amplified fields and COM excursion iSCI in the Null field.

Within participants with iSCI, the initiation step MOS$_{\text{min}}$ (Fig. 3) was significantly larger in the Damped (p = 0.000) and Amplified (p = 0.000) fields compared to the Null field, and in the Damped compared to Amplified field (p = 0.042). These larger MOS$_{\text{mins}}$ values occurred with significantly less COM excursion than in the Null field despite lower and higher peak COM velocities in the Damped and Amplified fields compared to the Null field, respectively.

Within participants without iSCI, there were no significant differences between fields on the initiation step MOS$_{\text{min}}$. However, COM excursion was smaller in the Damped field compared to the Null and Amplified fields and slower in the Damped than Null field.

### 3.4 Execution Step

On the execution step (Fig. 4), there were no significant differences in MOS$_{\text{min}}$ or stepping metrics between groups. Within participants with iSCI, MOS$_{\text{min}}$ was significantly larger in the Damped (p = 0.024) and Amplified (p = 0.018) fields compared to the Null field. Step width was different between all fields in the iSCI group (Damped > Amplified > Null), and peak COM velocity was greater in the Damped than Null field.

Similarly, participants without iSCI had significantly larger MOS$_{\text{min}}$ (Fig. 4) in the Damped (p = 0.000) and Amplified (p = 0.000) fields compared with the Null field as well as different step widths (Damped > Amplified > Null). Individuals without iSCI showed greater peak COM velocity in the Damped field compared to the Amplified field.

### 3.5 Termination Step

On the termination step (Fig. 5), participants with iSCI had a larger MOS$_{\text{min}}$ than their peers without iSCI in the Damped field (p = 0.000) but did not significantly differ in the other fields. Interestingly, there were no significant differences in step width between groups or fields, and thus, the larger termination step MOS$_{\text{min}}$ in the Damped field is likely attributable to reduced COM excursion and peak COM velocity in persons with iSCI. The adaptation to the Damped field appears to largely occur as increased step width on the preceding execution step. People with iSCI tended to step similarly wide on the execution step, but peak COM velocity was smaller across fields compared the participants without iSCI.

Within participants with iSCI, the termination step MOS$_{\text{min}}$ was larger in the Damped (p = 0.003) and Null (p = 0.006) fields compared to the Amplified field. COM excursion was different between all fields, with the smallest values in the Damped field and largest in the Amplified field (Fig. 5). Peak COM velocity was also smaller in the Damped field compared to the Null and Amplified fields.
Within participants without iSCI, the termination step MOS$_{\text{min}}$ (Fig. 5) was significantly different between all fields, with the smallest in the Damped field ($p = 0.000$ between all fields) and largest in the Amplified field. COM excursion was also different between all fields, but unlike the iSCI group, the smallest excursions were in the Damped field and the largest were in the Null field. Peak COM velocity was also smaller in the Damped field than Null field.

4. Discussion

Maneuvering is an essential component of walking, yet its complexity makes it difficult to characterize and address stability of this behavior, particularly when injury such as iSCI imparts significant coordination and strength deficits. This study investigated the stability and stepping strategies persons with and without iSCI use to laterally maneuver without an external force field and in the presence of Damped and Amplified force fields. These fields modified the stability requirements to first transition from forward walking into a lateral maneuver and then arrest the lateral maneuver to resume forward walking.

4.1 Margin of Stability Between Groups

Study of lateral maneuvers in persons with and without iSCI has revealed trade-offs between stability and maneuverability (1, 8), and the current study adds to our understanding of people’s preferences and/or abilities. When laterally maneuvering, individuals must weigh minimizing mechanical energy costs, maintaining stability, and producing adequate lateral ground-on-foot force to maneuver. Overall trends showed a larger MOS$_{\text{min}}$ in participants with iSCI compared to those without iSCI as expected (Fig. 2). However, large variation within the iSCI group appears to shield any difference in MOS$_{\text{min}}$ between groups in the Null field, particularly on initiation and termination steps (Figs. 3 & 5). The difference in MOS$_{\text{min}}$ was only significant in the Damped and Amplified fields on the initiation step and in the Damped field on the termination step. Cautious response to the force fields by persons with iSCI - regardless of their direction - may have emphasized the larger MOS$_{\text{min}}$ values that yielded significance compared to their peers without iSCI. While it may be expected for individuals with iSCI to increase cautiousness and therefore MOS$_{\text{min}}$ in the Amplified field, the larger MOS$_{\text{min}}$ is surprising in the Damped field, as a previous study of straight walking (6) showed adaptation to a smaller MOS in a Damped field in persons with and without iSCI. The complexity of maneuvering, however, may have added enough challenge to prompt adaptation of a more cautious strategy with iSCI. Therefore, individuals with iSCI may have elected a larger initiation step MOS$_{\text{min}}$ in the force fields out of an abundance of caution, whereas those without iSCI may have taken advantage of the Damped field, relying on its stabilizing contribution to maneuver initiation and termination, and permitted the Amplification field to assist in breaching stabilization to initiate the maneuvers.

4.2 Initiation Step
Based on previous work on maneuvers without force fields, we expected individuals to have a smaller MOS on the initiation step, which may allow for a faster maneuver but introduces stability vulnerability (4, 8). As anticipated, the MOS$_{\text{min}}$ on the initiation step was smallest in nearly all conditions (p < 0.05 for all combinations of groups, steps, and fields except for the initiation versus termination comparison in the Damped field and in the Amplified field within iSCI). This behavior likely indicates that reduced stability in anticipation of a maneuver in a known direction was considered an acceptable risk in exchange for enhancing maneuverability upon initiation of the task. Both groups did not have a significantly smaller MOS$_{\text{min}}$ on the initiation step compared to the termination step in the Damped field, however, but for different reasons. Persons with iSCI had a relatively larger MOS$_{\text{min}}$ and step width on the initiation step (significantly larger in iSCI compared to controls, as well, Fig. 3), while persons without iSCI had a relatively smaller MOS$_{\text{min}}$ on the termination step. On the initiation step, the presence of a force field with iSCI, though predictable, may have increased cautiousness, whereas those without iSCI may have taken advantage of the Damped field by relying on its stabilizing contribution.

Interestingly, the larger MOS$_{\text{min}}$ in the Amplified field within the iSCI group occurred with conflicting COM motion. Individuals with iSCI exhibited smaller COM excursions but greater peak COM velocity in the Amplified field than in the Null field. The smaller excursion may have contributed to the larger MOS$_{\text{min}}$, but a greater peak COM velocity suggests COM movements may have actually been less controlled. In contrast, in the Null field, participants with iSCI had large COM excursions, which were significantly greater than in persons without iSCI (Fig. 3). This change may account for the significant decrease in excursion seen in the Amplified field. Thus, maneuvering in force fields may be a means for facilitating persons with iSCI to practice maneuvering with smaller COM excursions during the initiation step, which is not only more similar to persons without iSCI, but potentially more stable, safe, and energetically efficient (9).

Contrary to the hypothesis, participants without iSCI did not change their MOS$_{\text{min}}$ between fields on the initiation step. Given individuals’ capacity for generating corrective lateral impulses, the fields may have been perceived as manageable without any advantage gained though modulation of MOS$_{\text{min}}$.

### 4.3 Execution Step

On the execution step, both groups utilized greater MOS$_{\text{min}}$ and wider steps in the non-zero fields (Fig. 4). Despite the increase in energetic cost (1), it was hypothesized that the execution step in the Damped field would have wide side-stepping that can yield a large MOS and minimize the disturbance to frontal plane angular momentum associated with large lateral ground-on-foot force (such as that needed to maneuver against a Damped field). The opposite was hypothesized for the Amplified field, however, where the field acts in the direction of the maneuver (i.e. assisting it) so a smaller lateral ground-on-foot force magnitude is needed in the direction of the maneuver. The increases in execution step MOS$_{\text{min}}$ and step width in the Amplified field may have been a method to oppose any excess movements emphasized by the field (possibly in anticipation of the braking necessary on the subsequent termination step), or failure to take advantage of the excursion assistance. This stabilizing behavior, surprisingly, did not occur more
markedly in persons with iSCI. The similarity between groups may have been due to the relative novelty of the amplifying field; providing further practice in subsequent studies may better reveal differences on the execution step if ability limits persons with iSCI to such a stabilizing strategy but not those without iSCI.

### 4.4 Termination Step

On the termination step, the contribution of the force fields to the maneuver task reverses. That is, the Damped field assists in lateral braking (lateral ground-foot force opposite in direction to the maneuver), while the Amplified field opposes and necessitates more self-produced braking. This motivated the hypothesis that the termination step MOS\(_{\text{min}}\) would be smaller in the Damped field than in the Null, however, experimentally MOS\(_{\text{min}}\) in the Damped field was not significantly different from Null for those with iSCI (Fig. 5). For both populations, COM excursion and peak velocity were smaller in the Damped field compared to Null field, indicating the larger MOS\(_{\text{min}}\) on the termination step was likely a consequence of the field.

With the proposed challenge to maneuver termination, it was hypothesized termination step MOS\(_{\text{min}}\) would be greater in the Amplified field than in the Null. The termination step MOS\(_{\text{min}}\) in the Amplified field showed different relative behavior in each group. Participants in both groups had similar MOS\(_{\text{min}}\) in the Amplified field; however, relative to the Null field, those without iSCI had a larger MOS\(_{\text{min}}\) while participants with iSCI had a smaller MOS\(_{\text{min}}\) (Fig. 5). Individuals without neurological injury behaved consistently with the hypothesis that a larger MOS\(_{\text{min}}\) would be used to avoid target overshoot in the destabilizing field. The larger MOS\(_{\text{min}}\) occurred with similar step width but reduced COM excursion, demonstrating what seems to be a controlled maneuver without the need for adapted foot placement. The opposite was seen in those with iSCI, where the reduced MOS\(_{\text{min}}\) occurred with greater COM excursion and, again, consistent foot placement. Assuming that individuals with iSCI would have reduced COM excursion like those without iSCI if they were capable, this difference between the groups highlights maneuver termination in the Amplified field as a particularly challenging task. Although specific strength and/or coordination deficits are not clear, the reduced stability apparent with iSCI in a task where their peers without iSCI tend to increase stability suggests a deficit that may be addressable with practice in such an environment.

### 4.5 Meaningful Maneuver Measurements & Limitations

The ability of the current study to successfully differentiate behaviors between groups and force field conditions provides valuable perspectives on the study of walking maneuvers in general. Key factors in creating maneuvers that could be compared across groups and repetitions were the constraints placed on the maneuver task. At the risk of becoming non-representative of maneuvers during natural ambulation, carefully chosen control of protocol factors was necessary. This study included relatively comparable repetitions of the task by cueing maneuvers of specific, predictable direction and magnitude with relatively uncertain timing, although maneuvers were cued at a consistent phase of the gait cycle. This attribute in particular successfully prevented the use of cross-over steps, which would have been...
considered incompatible for comparison within this study. The differences and similarities observed between persons with iSCI and their peers without iSCI highlight potential areas for further focused intervention and study. Specifically, this work demonstrated value in the use of a maneuver task with different force fields to expose behavioral differences, although it is difficult to ascertain whether the observed behaviors in the current study more strongly reflect personal preferences or boundaries in abilities. The instruction on urgency with which to complete the maneuver (in this study, “as safely and efficiently as possible”) likely provided the most latitude for personal interpretation and preference in behavior. This was particularly evident among persons without iSCI in the damped field, where it was assumed all participants were capable of performing the task without multiple intermediate steps but in some cases, took more than one to reach the target lane. Given the motivation this study provides for the maneuver paradigm as a microscope for understanding stepping strategies, further study manipulating the urgency or number of intermediate steps with which participants perform maneuvers would unpack important questions of ability and preferences that were beyond the scope of the current study.

5. Conclusions

This study used lateral force fields during a walking maneuver task to better understand how persons with and without iSCI adapt their stepping strategies under varied stability conditions. In addition to generally characterizing the strategies used by each group, it provides insight on how to potentially provide persons with iSCI practice that may improve the safety and stability of their maneuvers. The amplified force field, that pushed people in the direction they were already moving, resulted in persons with iSCI using a significantly larger $MOS_{\text{min}}$ than persons without iSCI to initiate the maneuver. Persons with iSCI used a larger step width that increased their $MOS_{\text{min}}$, but their resultant COM excursion was actually similar to persons without iSCI – a behavior that may be more appropriate for maneuvering without excessive COM excursion. In addition, persons with iSCI were capable of but challenged by terminating maneuvers in the amplified field, as evidenced by their decreased $MOS_{\text{min}}$ on this step versus the increased $MOS_{\text{min}}$ on the same step in persons without iSCI. Thus, practicing maneuvers in an amplified field may be valuable as an intervention aimed at improving COM excursion control and maneuver termination ability in persons with iSCI.

Abbreviations

10MWT
ten-meter walk test
AIS
American Spinal Injury Association Impairment Scale
BOS
base of support
COM
center of mass
FGA
functional gait assessment
iSCI
incomplete spinal cord injury
LEMS
Lower Extremity Motor Score
MOS
margin of stability
MOS\textsubscript{min}
minimum margin of stability
WISCI II
walking index for spinal cord injury

Declarations

Ethics approval and consent to participate

All participants gave written informed consent prior to beginning the study to either the Research Physical Therapist, Jane Woodward or the Principal Investigator, Dr. Keith Gordon. The Northwestern University Institutional Review Board approved the protocol: IRB# STU00204732. The Edward Hines Jr. Veterans Administration Hospital Institutional Review Board approved the protocol: IRB # 985188-17.

Consent for publication

The manuscript contains no individual data.

Availability of data and materials

The dataset generated and analyzed during the current study is available in the ARCH Northwestern University Institutional Repository, https://doi.org/10.21985/n2-x1kd-xx86.

Competing interests

The authors declare no competing interests.

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Authors’ Contributions
JW recruited subjects, collected clinical outcome measures, and managed data collections. KEG recruited subjects, managed data collections, conceived the experimental design, and contributed to interpretation of results and manuscript editing. WLO managed data collection, experimental design and protocol implementation, completed all data analysis, and drafted the manuscript. TC contributed to data collection, analysis, and interpretation, and edited the manuscript. All authors read and approved the final manuscript.

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**References**

1. Acasio J, Wu M, Fey NP, Gordon KE. Stability-maneuverability trade-offs during lateral steps. Gait Posture. 2017;52:171-7.
2. Musselman K, Brunton K, Lam T, Yang J. Spinal cord injury functional ambulation profile: a new measure of walking ability. Neurorehabilitation and neural repair. 2011;25(3):285-93.
3. Brotherton SS, Krause JS, Nietert PJ. Falls in individuals with incomplete spinal cord injury. Spinal Cord. 2007;45(1):37-40.
4. Wu M, Matsubara JH, Gordon KE. General and Specific Strategies Used to Facilitate Locomotor Maneuvers. PLoS One. 2015;10(7):e0132707.
5. Wu MB, GL; Woodward, JL; Bruijn, SM; Gordon, KE. A novel Movement Amplification environment reveals effects of controlling lateral centre of mass motion on gait stability and metabolic cost. Royal Society Open Science. 2020;7(1):190889.
6. Wu M, Brown G, Gordon KE. Control of locomotor stability in stabilizing and destabilizing environments. Gait Posture. 2017;55:191-8.
7. Hof AL, Gazendam MG, Sinke WE. The condition for dynamic stability. J Biomech. 2005;38(1):1-8.
8. Viramontes C, Acasio J, Kim J, Gordon KE. Speed impacts frontal-plane maneuver stability of individuals with incomplete spinal cord injury. Clinical Biomechanics. 2020;71:107-14.
9. Matsubara JH, Wu M, Gordon KE. Metabolic cost of lateral stabilization during walking in people with incomplete spinal cord injury. Gait Posture. 2015;41(2):646-51.
10. Brown G, Wu MM, Huang FC, Gordon KE. Movement augmentation to evaluate human control of locomotor stability. Conf Proc IEEE Eng Med Biol Soc. 2017;2017:66-9.
11. Wu MM, Brown GL, Kim K-YA, Kim J, Gordon KE. Gait variability following abrupt removal of external stabilization decreases with practice in incomplete spinal cord injury but increases in non-impaired individuals. Journal of neuroengineering and rehabilitation. 2019;16(1):4.
12. Bowden MG, Behrman AL. Step Activity Monitor: accuracy and test-retest reliability in persons with incomplete spinal cord injury. Journal of Rehabilitation Research & Development. 2007;44(3).
13. Lam T, Noonan VK, Eng JJ. A systematic review of functional ambulation outcome measures in spinal cord injury. Spinal cord. 2008;46(4):246-54.

14. van Hedel HJ, Wirz M, Dietz V. Assessing walking ability in subjects with spinal cord injury: validity and reliability of 3 walking tests. Archives of physical medicine and rehabilitation. 2005;86(2):190-6.

15. Gordon K, Kahn J, Ferro S, Frank L, Klashman L, Nachbi R, et al. Reliability and Validity of the Functional Gait Assessment in Spinal Cord Injury. Archives of Physical Medicine and Rehabilitation. 2016;97(10):e87.

16. Burns AS, Delparte JJ, Patrick M, Marino RJ, Ditunno JF. The reproducibility and convergent validity of the walking index for spinal cord injury (WISCI) in chronic spinal cord injury. Neurorehabil Neural Repair. 2011;25(2):149-57.

17. Marino RJ, Scivoletto G, Patrick M, Tamburella F, Read MS, Burns AS, et al. Walking index for spinal cord injury version 2 (WISCI-II) with repeatability of the 10-m walk time: Inter- and intrarater reliabilities. Am J Phys Med Rehabil. 2010;89(1):7-15.

Tables

Due to technical limitations, table 1 is only available as a download in the Supplemental Files section.