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Metabolic cost of lateral stabilization during walking in people with incomplete spinal cord injury

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ABSTRACT

People with incomplete spinal cord injury (iSCI) expend considerable energy to walk, which can lead to rapid fatigue and limit community ambulation. Selecting locomotor patterns that enhance lateral stability may contribute to this population's elevated cost of transport. The goal of the current study was to quantify the metabolic energy demands of maintaining lateral stability during gait in people with iSCI. To quantify this metabolic cost, we observed ten individuals with iSCI walking with and without external lateral stabilization. We hypothesized that with external lateral stabilization, people with iSCI would adapt their gait by decreasing step width, which would correspond with a substantial decrease in cost of transport. Our findings support this hypothesis. Subjects significantly ($p < 0.05$) decreased step width by 22%, step width variability by 18%, and minimum lateral margin of stability by 25% when they walked with external lateral stabilization compared to unassisted walking. Metabolic cost of transport also decreased significantly ($p < 0.05$) by 10% with external lateral stabilization. These findings suggest that this population is capable of adapting their gait to meet changing demands placed on balance. The percent reduction in cost of transport when walking with external lateral stabilization was strongly correlated with functional impairment level as assessed by subjects' scores on the Berg Balance Scale ($r = 0.778$) and lower extremity motor score ($r = 0.728$). These relationships suggest that as functional balance and strength decrease, the amount of metabolic energy used to maintain lateral stability during gait will increase.

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1. Introduction

During gait people with incomplete spinal cord injury (iSCI) have oxygen consumption rates ~50–225% higher than non-disabled individuals [1], with metabolic cost of transport (COT) increasing with impairment level [2]. This energetically inefficient gait is associated with decreased social participation and quality of life [3,4]. Thus, identifying specific factors that contribute to elevated COT could aid the development of targeted therapies to improve wellbeing.

Gait stability is crucial for community ambulation. Research suggests that human walking is passively unstable in the frontal plane and therefore requires active control [5]. An important strategy for maintaining lateral stability is step-to-step foot placement. Taking wider steps creates a larger lateral base of support (BOS) and may increase the threshold of perturbation before a corrective step is required to maintain balance [6]. However, increasing step width increases the mechanical work required to redirect the center of mass (COM) at each step [7]. A simple model suggests that COT will increase with the square of step width [8]. Thus, increasing lateral stability by increasing step width comes with a potentially severe energetic penalty.

People with iSCI may choose gait patterns that increase stability even if this action increases energetic cost. Selecting general strategies that increase passive stability every step (e.g. increasing step width) is desirable when sensory and motor impairment limit the ability to maintain lateral stability via step-to-step corrective foot placements. Individuals with iSCI exhibit significant step width variability [9] due to both corrective actions and poor motor control. Controlling step width variability may also impart an energetic cost [10]. While neuromuscular deficits limit the available locomotor strategies one can perform, there is evidence that people with iSCI can alter their gait patterns in response to varying environmental factors [11,12] and task goals [13].

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Table 1
Subject information.

Subject	Gender	Age (years)	Years post SCI	Weight (kg)	SCI level	AIS	Speed (m/s)	LEMS	BBS	10 MWT (m/s)
1	M	50	17.3	79.4	C5	D	0.5	49	48	1
2	F	54	13.3	68.6	T8	D	0.5	43	55	1
3	M	47	5.4	81.8	C7	D	0.6	48	56	1.8
4	M	65	9.1	93.7	C3	D	0.1	37	36	0.3
5	M	55	6.3	83.8	C2	D	0.2	46	50	0.5
6	M	41	8.5	97.1	L3	D	0.2	33	51	1.3
7	M	59	19.1	80.3	C5	D	0.6	45	51	1.2
8	M	52	6.6	91.4	C6	D	0.4	39	46	0.8
9	M	67	3.9	75	C5	D	0.7	46	53	1.5
10	M	72	1.9	64.4	C4	D	0.9	48	56	1.5
Mean ± SD		56.2 ± 9.6	9.1 ± 5.7	81.6 ± 10.6			0.5 ± 0.2	43.4 ± 5.4	50.2 ± 6.0	1.1 ± 0.5

SCI level: level of spinal cord lesion; AIS: American Spinal Injury Association Impairment Scale classification; speed: preferred treadmill walking speed; LEMS: lower extremity motor score; BBS: Berg Balance Scale; 10 MWT: 10 Meter Walk Test.

The energetic cost of maintaining lateral stability during walking can be quantified by measuring oxygen consumption when this requirement is reduced through external lateral stabilization [14,15]. With external lateral stabilization, unimpaired individuals decrease step width and reduce their COT ~3–7% [14–16]. Our purpose was to quantify the metabolic energy cost of maintaining lateral stability in people with iSCI. We hypothesized that people with iSCI would adapt to external lateral stabilization by decreasing step width, which in turn would result in a substantial decrease in COT. In addition, we hypothesized that standard clinical measures of function and balance would be related to the metabolic energy required for lateral stabilization.

2. Methods

2.1. Participants

Ten subjects with chronic motor iSCI participated in this study (9 male; age: 57 ± 10 years; all AIS D and >1 year post injury) (Table 1). Subjects gave written informed consent prior to participation. Northwestern University Institutional Review Board approved the protocol. With the exception of iSCI, subjects had no other neurological impairments. All subjects could walk without assistive devices for 5 min at their preferred speed. Subjects did not alter medications for this study; one subject reported taking antispastic medication.

2.2. Experimental setup

Subjects walked on a treadmill with no handrails (Tuff Tread, Willis, TX) while wearing a safety harness (Aretech, Ashburn, VA). The safety harness did not provide bodyweight support or restrict lateral movement.

During specific trials, subjects received external lateral stabilization. External lateral stabilization was applied by tensioned springs (Theraband, Akron, OH) attached bilaterally to a belt worn snugly around the pelvis [14]. The setup had an effective stiffness of 1027 N/m and damping coefficient of 2.3 Ns/m, determined by oscillating a mass between the springs [14]. Each spring was anchored to a low-friction trolley mounted on horizontal rails to allow fore-aft movement [16] (Fig. 1). To allow arm swing, the springs were attached to ropes routed around PVC pipes. The ropes attached to the belt at four points half-way between the midline and lateral border of the pelvis to minimize resistance to hip hiking. The springs ran parallel to the ground during standing.

2.3. Measurements

We measured lower body kinematics and oxygen consumption. We used a 10 camera motion capture system (Qualisys, Gothenburg, Sweden) to record 3D motion of 11 reflective markers placed on the second sacral vertebra, and bilaterally on the greater trochanter, lateral knee joint line, calcaneus, 5th and 2nd metatarsal. Kinematic data were recorded at 100 Hz. We recorded breath-to-breath oxygen consumption using a portable gas analysis system (Cosmed, Chicago, IL).

2.4. Experimental protocol

Subjects participated in two experimental sessions. During the first session, clinical tests were administered, preferred treadmill walking speed was determined, and subjects practiced walking with and without external lateral stabilization. Clinical tests included the lower extremity motor score (LEMS) portion of the American Spinal Injury Association Impairment Scale (AIS), the Berg Balance Scale (BBS), and the 10 Meter Walk Test (10 MWT) performed at subjects' maximum speed. Then, preferred treadmill walking speed was determined as the speed subjects felt most comfortable maintaining for 5 min. Finally, subjects practiced walking with and without external lateral stabilization for 5 min.

The second session was completed 2–5 days later. Subjects first re-acclimated to the task by walking with external lateral stabilization for 2 min. Subjects then rested for >2 min. Next, we measured oxygen consumption during 5 min of quiet standing

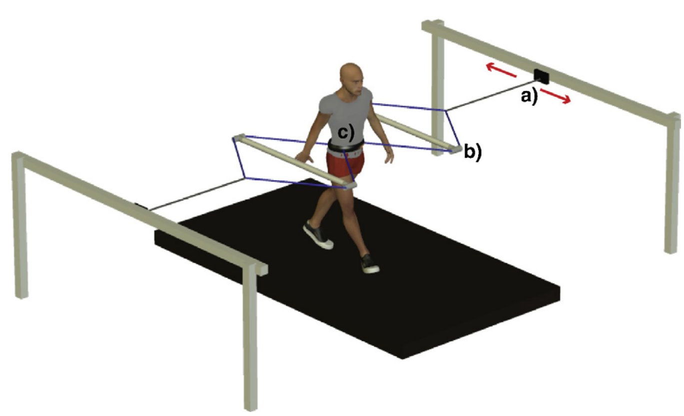

Fig. 1. External lateral stabilization setup. (a) Springs are anchored to low-friction trolleys that allow fore-aft movement of the subject. (b) To allow unrestricted arm swing, rope connected to the springs was routed around lightweight PVC tubes. (c) The rope is attached to a snug belt worn by the subject.

without external lateral stabilization. Finally, subjects completed two 5-min walking trials, one with and one without external lateral stabilization. The order of the trials was randomized. Walking was performed at subjects' preferred treadmill speed. A rest period of >2 min was given between trials. Subjects were instructed to walk in a manner that was comfortable and to not resist the stabilization.

2.5. Data analysis

Kinematic and metabolic data were recorded during the last 2 min of each 5-min trial to allow subjects time to reach steady-state. All motion capture data was gap-filled and smoothed with a 2nd order Butterworth filter with a cut-off frequency of 10 Hz. We identified heel strike and toe-off using marker data and visually inspected the data to ensure accuracy of this method.

Average metabolic power (W) during quiet standing and each walking trial was calculated using the standard relationship of 20.9 W for each milliliter of oxygen consumed per second [17]. To calculate the metabolic power of walking, the average metabolic power during standing was subtracted from the total metabolic power during walking. COT was calculated by normalizing the metabolic power of walking to bodyweight and speed.

Step width and length were defined as the medio-lateral and fore-aft distance, respectively, between calcaneus markers at heel strike. Step width and length variability were calculated from the standard deviations of each measure over all recorded steps.

Lateral extrapolated center of mass position (XCOM) and lateral margin of stability (MOS) were calculated using the following equations [6]:

$$XCOM = COM + \frac{\dot{COM}}{\sqrt{g/l}}$$
$$MOS = BOS - XCOM$$

We used the 5th metatarsal marker to identify the lateral base of support (BOS), and the 2nd sacral vertebrae marker to estimate lateral COM location [18]. Leg length (l) was defined as 1.3 * greater trochanter height.

We calculated the minimum MOS each step and calculated an average minimum MOS for each subject and condition. Finally, we calculated the peak-to-peak lateral XCOM excursion during each stride and calculated an average value for each subject and condition.

2.6. Statistical analysis

All measures (COT, step width, step width variability, step length, step length variability, minimum MOS, and XCOM lateral excursion) were compared with and without external lateral stabilization using two-sided paired t-tests. Differences were considered significant at $p < 0.05$. In addition, we calculated Pearson's correlation coefficients relating the change in COT with and without external lateral stabilization to BBS score, LEMS, 10 MWT, and preferred treadmill speed. We checked the significance of the critical value of the correlation coefficient using a two-tailed test. p-Values <0.05 were deemed significant.

3. Results

All subjects except one *decreased* their COT with external lateral stabilization. Subject 6 did not appear comfortable walking with external lateral stabilization and exhibited a 36% *increase* in COT, which was 4.5 interquartile ranges from the median COT % change value. Thus, we treated this subject as an outlier and excluded the data from all analyses. For the remaining subjects, COT decreased 10% on average with external lateral stabilization, from 7.9 ± 1.5 to 7.0 ± 1.2 J/kg/m (p = 0.03) (Fig. 2a).

Subjects made several significant changes in their frontal plane kinematics with external lateral stabilization. Minimum MOS decreased significantly (p = 0.0005), changing 25% from 0.070 ± 0.003 m without to 0.053 ± 0.003 m with lateral stabilization (Fig. 2b). Step width decreased significantly (p = 0.007) with external lateral stabilization, narrowing 22% from 0.14 ± 0.02 units of leg length (L) to 0.11 ± 0.02 L (Figs. 2c and 3). Step width variability significantly decreased (p = 0.007) by 18% from 0.032 ± 0.004 L to 0.026 ± 0.003 L with lateral stabilization (Fig. 2d). There was no significant change (p = 0.4397) in XCOM lateral excursion with (0.17 ± 0.04 m) or without (0.16 ± 0.04 m) external lateral stabilization (Fig. 3).

Subjects did not change sagittal plane kinematics with external lateral stabilization. Step length was 0.38 ± 0.05 L without and 0.38 ± 0.05 L with stabilization (p = 0.6) (Fig. 2e). Step length variability was 0.05 ± 0.00 L without and 0.05 ± 0.01 L with stabilization (p = 0.8) (Fig. 2f).

We found strong, significant correlations between COT % change with external lateral stabilization and both LEMS (r = 0.728) (p = 0.026) and BBS score (r = 0.778) (p = 0.014) (Fig. 4a and b). Correlations between COT % change and 10 MWT (r = 0.384) (p = 0.322) and preferred treadmill speed (r = 0.463) (p = 0.210) were not significant (Fig. 4c and d).

4. Discussion

When the demands of lateral stabilization were reduced, individuals with iSCI made significant decreases in step width, step width variability, and minimum MOS. These gait adaptations corresponded with a 10% decrease in COT. As functional

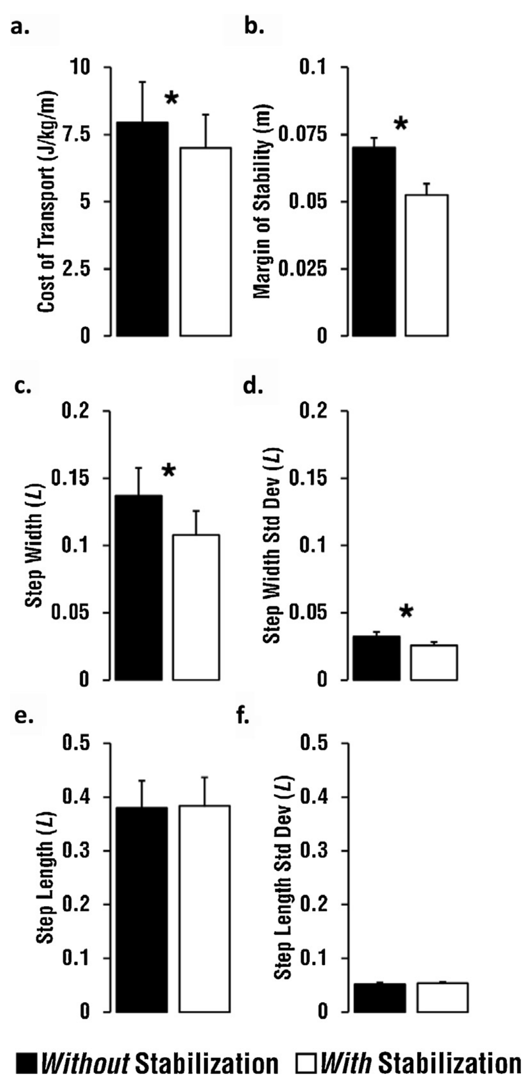

Fig. 2. Group means ± standard error of (a) cost of transport, (b) margin of stability, (c) step width, (d) step width variability, (e) step length, and (f) step length variability with and without external lateral stabilization. (L) Indicates units of leg length. (*) Indicates a significant difference ($p < 0.05$).

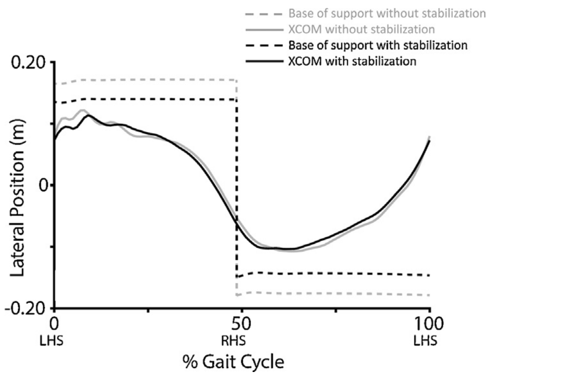

Fig. 3. Average gait cycle from one subject (subject 5) showing base of support (dashed lines) and XCOM position (solid lines) when walking without external lateral stabilization (gray lines) and with external lateral stabilization (black lines). LHS: left heel strike; RHS: right heel strike.

impairment increased on the BBS and LEMS, the metabolic cost of lateral stabilization tended to increase. These findings support our hypotheses that people with iSCI will adapt their gait in response to changing demands placed on dynamic balance, and that the metabolic cost associated with lateral stability is substantial for this population.

We found that people with iSCI modulated step width in response to changes in lateral stability requirements. With external stabilization, subjects decreased their minimum lateral MOS by 24%. This change was primarily due to narrowing step width and not to changes in XCOM excursion. If changes in MOS were due solely to the external lateral stabilization and not to active modulations, we would expect the opposite of what occurred (the springs would directly reduce XCOM excursion, not step width). As such, it appears that subjects made active changes in step width when lateral stabilization requirements were decreased.

The absence of step length changes with lateral stabilization was consistent with previous observations [16]. However, step width reductions 2–3 times the amount observed in the current study have been reported [14,15,19]. With very narrow steps, the swing limb must be controlled to avoid collisions with the stance limb. Controlling the swing limb may be challenging for individuals with iSCI. As such, individuals may limit reductions in step width to minimize the risk of tripping if their limbs were to collide. Given that lateral COM displacements and velocities will change in proportion to step width [8] the limited reductions in step width we observed may partially explain why lateral XCOM excursions did not change. In previous studies, greater decreases in step width with external lateral stabilization may have contributed to larger decreases in lateral COM excursion [14]. In the current study, decreases in step width variability were also smaller than previous reports [14,16,19]. Step width variability is a result of corrective foot placements and sensory-motor noise. Because external stabilization should decrease the need for corrective foot placements but not directly impact sensory-motor noise, it is not surprising that individuals with iSCI would exhibit smaller reductions in step width variability than non-impaired subjects.

The average COT for individuals with iSCI (7.9 J/kg/m) decreased by 0.9 J/kg/m with external lateral stabilization. This is a substantial amount of energy consumed for both walking and lateral stabilization. For comparison, COT for non-impaired subjects walking at 0.5 m/s (which is comparable to speeds used in the current study) is ~3.0 J/kg/m [20], and although it has not been measured during such slow walking speeds, the energy non-impaired individuals require for lateral stabilization has been estimated to be ~3–7% [14–16] of the total COT. Rapid fatigue is a major factor limiting community ambulation for individuals with iSCI [21]. Our results suggest that the metabolic energy required for lateral stabilization makes a substantial contribution to the elevated COT individuals with iSCI experience.

Ambulatory individuals with iSCI display unique gait characteristics compared to non-impaired populations. Individuals with iSCI rely more on proximal joints and less on distal joints to power locomotion [22,23]. Reliance on proximal muscle groups may increase COT [24]. Frontal plane trunk and pelvis motion tends to be greater than in non-impaired subjects, but it is not clear if this motion is compensatory, as lateral excursions do not change in response to walking at varying inclines [25]. In the current study,

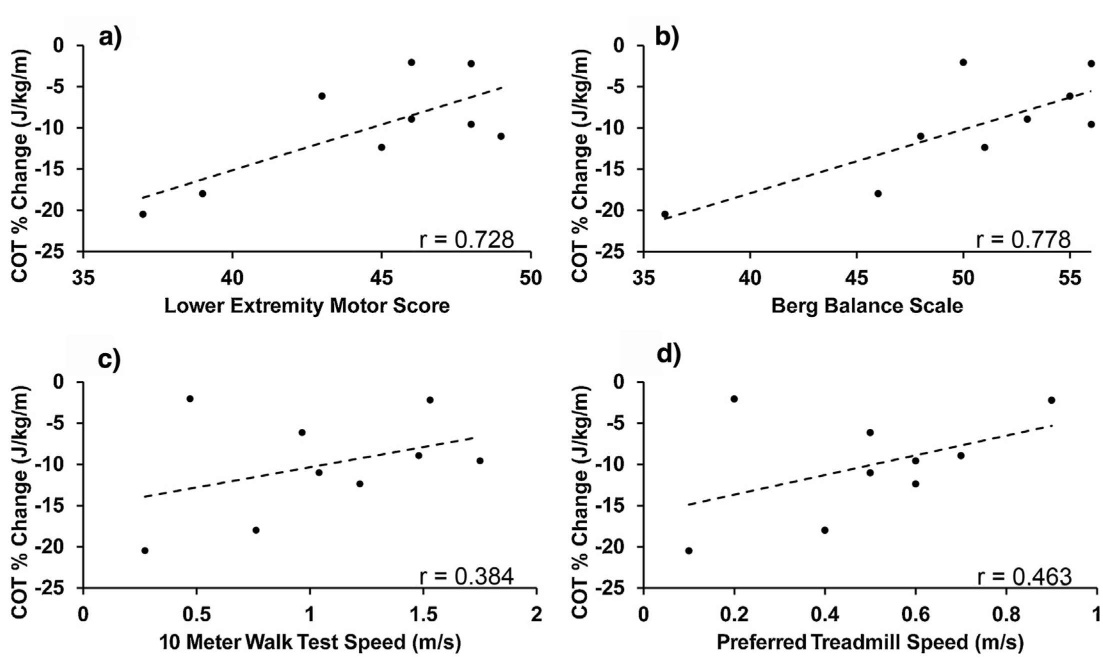

Fig. 4. Pearson correlation coefficients between decrease in cost of transport with external stabilization (COT % change) and (a) lower extremity motor score, (b) Berg Balance Scale score, (c) 10 Meter Walk Test speed, and (d) preferred treadmill speed.

compensatory frontal plane pelvic motions (e.g. hip hiking to assist leg swing) would have been resisted by external lateral stabilization, increasing the mechanical work and metabolic cost of these motions. If compensatory motions were resisted, our results may have *under*estimated the true metabolic cost of lateral stabilization. As such, it is important to recognize the potential limitations of using external lateral stabilization to quantify lateral stabilization costs in impaired populations. For example, this methodology was ineffective for determining the metabolic energy costs of lateral stabilization for transfemoral amputees because the setup impeded compensatory mechanisms [26]. In addition, reduced metabolic cost with external lateral stabilization in individuals with iSCI may have been due to factors other than reducing the mechanical work performed to redirect lateral COM motion each step [8] or to control step width variability [10]. Stabilization may have allowed individuals to decrease other sources of inefficient movement such as cocontractions and jerky movements [27]. As these factors were not quantified, this is a potential limitation in interpreting the results of this study.

Subjects with poor balance control, indicated by lower BBS scores, experienced the greatest COT % decreases with external stabilization. This suggests that as balance control decreases, the metabolic energy required for lateral stabilization increases. Because subjects were all relatively high functioning, there may have been a ceiling effect of the BBS score [28] in assessing high level balance, which could have reduced the strength of the correlation observed. Unfortunately, the range of impairment levels was limited in the current study because subjects were required to walk continuously without assistance for 5 min to measure VO_2 consumption. The LEMS also had a high correlation with COT % decrease. While the LEMS measures muscle strength, a higher score is likely correlated with more sparing of motor and sensory pathways, which contribute to balance. The correlation of 10 MWT and preferred treadmill speed to COT % decrease was weak, indicating that walking speed was not a strong indicator of the metabolic energy required for lateral stabilization. This is in agreement with recent findings that the metabolic cost of lateral stability is independent of walking speed in non-impaired populations [16]. A few subjects had preferred treadmill walking speeds <0.3 m/s. This very slow gait likely reduced the challenges of controlling the momentum of the limbs and trunk and may be a mechanism individuals with iSCI use to increase stability [29]. Changes in dynamics occurring at very slow walking speeds may contribute to the weak correlations observed between speed and the COT % decrease with external stabilization.

People can achieve lateral stability through a combination of general (present at every step) stabilization strategies that improve their ability to withstand any lateral perturbation (e.g. increasing step width) and through specific (only present when needed) stabilization strategies that improve their ability to response to specific perturbations (e.g. corrective foot placement). While both general and specific strategies are valuable, for individuals with iSCI who have challenges sensing and responding to perturbations, stabilization is likely achieved through general stabilization strategies that do not depend on accurate detection and reaction to perturbations. As demonstrated in the current study, a consequence of choosing stabilization strategies that are present every step is an associated metabolic cost.

That people with iSCI can adapt their gait patterns in response to changing demands on balance may have implications for gait retraining. A study examining neurologically intact subjects learning to walk on a narrow beam found greater improvements in subjects who received no assistance than those who practiced with external lateral stabilization [30], suggesting that experiencing real-world dynamics may be important for learning locomotor balance. However, stability assistance may be valuable during the learning process when task difficulty is high [30]. In the current study, when subjects received external lateral assistance, they took narrower steps and decreased step width variability because requirements for active lateral stabilization were decreased. These changes suggest that high levels of external lateral stabilization could limit subjects' opportunities to experience real-world dynamics. Providing stability assistance may facilitate learning of some components of gait, such as sagittal plane stepping patterns, but may also limit the ability of an individual to learn to self-stabilize.

5. Conclusion

People with iSCI devote a substantial amount of energy to maintaining lateral stability. The amount of metabolic energy individuals used for maintaining lateral stability was strongly correlated with clinical tests of balance and lower extremity strength. Individuals with the greatest impairment used the most metabolic energy for maintaining lateral stability. When provided with external lateral stabilization, subjects responded by decreasing their step width, step width variability, and minimum MOS, demonstrating that this population is capable of modulating their gait patterns to meet changing demands placed on dynamic balance.

Conflict of interests

The authors declare no conflicts of interest.

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