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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

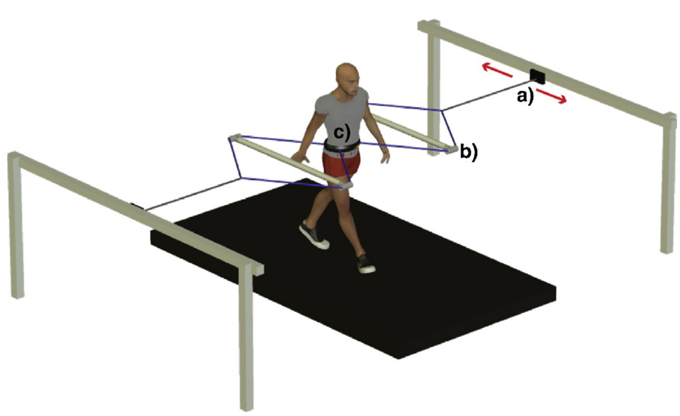

Fig. 1. External lateral stabilization setup. (a) Springs are anchored to low-friction trolleys that allow fore-aft movement of the subject. (b) To allow unrestricted arm swing, rope connected to the springs was routed around lightweight PVC tubes. (c) The rope is attached to a snug belt worn by the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