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Neuromuscular constraints on muscle coordination during overground walking in persons with chronic incomplete spinal cord injury

Heather B. Hayes [a], Stacie A. Chvatal [b], Margaret A. French [a], Lena H. Ting [b], Randy D. Trumbower [a,b,*]

[a] Dept. of Rehabilitation Medicine, Emory University, Atlanta, GA, USA
[b] Dept. of Biomedical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

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HIGHLIGHTS

- Persons with chronic incomplete spinal cord injury (iSCI) exhibit significant reduced muscle coordination during overground walking as compared to age-matched adults.
- Neuromuscular constraints following iSCI contribute to person-specific deficits in overground walking.
- Neuromuscular mechanisms underlying gait deficits may provide guidance for targeted SCI rehabilitation.

ABSTRACT

Objective: Incomplete spinal cord injury (iSCI) disrupts motor control and limits the ability to coordinate muscles for overground walking. Inappropriate muscle activity has been proposed as a source of clinically observed walking deficits after iSCI. We hypothesized that persons with iSCI exhibit lower locomotor complexity compared to able-body (AB) controls as reflected by fewer motor modules, as well as, altered module composition and activation.
Methods: Eight persons with iSCI and eight age-matched AB controls walked overground at prescribed cadences. Electromyograms of fourteen single leg muscles were recorded. Non-negative matrix factorization was used to identify the composition and activation of motor modules, which represent groups of consistently co-activated muscles that accounted for 90% of variability in muscle activity.
Results: Motor module number, composition, and activation were significantly altered in persons with iSCI as compared to AB controls during overground walking at self-selected cadences. However, there was no significant difference in module number between persons with iSCI and AB controls when cadence and assistive device were matched.
Conclusions: Muscle coordination during overground walking is impaired after chronic iSCI.
Significance: Our results are indicative of neuromuscular constraints on muscle coordination after iSCI. Altered muscle coordination contributes to person-specific gait deficits during overground walking.

1. Introduction

Incomplete spinal cord injury (iSCI) disrupts motor commands to spinal locomotor circuitry and often severely limits the ability to coordinate muscles for overground walking. While a healthy motor system is capable of coordinating many muscles spanning multiple joints for safe and efficient walking, this ability is impaired following iSCI. More than 75% of persons with motor incomplete injuries regain some walking capacity (van Hedel and Dietz, 2009), but many do not fully return to community walking (Field-Fote and Roach, 2011; van Hedel and Dietz, 2010). Unfortunately, we do not fully understand the underlying neuromuscular mechanisms that might contribute to this shortcoming nor how specific changes in muscle co-activity impair overground walking after chronic iSCI.

* Corresponding author at: Dept. of Rehabilitation Medicine, Emory University, School of Medicine, Atlanta, GA 30322, USA. Tel.: +1 404 727 3065; fax: +1 404 712 4130.
E-mail address: randy.trumbower@emory.edu (R.D. Trumbower).

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Inappropriate muscle activity is a source of many of the clinically observed walking deficits that emerge in persons with chronic iSCI (Gorassini et al., 2009; Maegele et al., 2002). Locomotor training studies often target impaired muscle activity timing, agonist–antagonist joint level muscle coactivity, and electromyography (EMG) burst durations in an effort to improve walking ability (Gorassini et al., 2009; Grasso et al., 2004; Ivanenko et al., 2003, 2004; Maegele et al., 2002; Visintin and Barbeau, 1994). However, these studies primarily focus on treadmill and body-weight support training and not overground walking. Although treadmill walking permits greater experimental control of walking conditions like speed and body-weight support, the ability to coordinate muscles during these more constrained tasks does not necessarily translate to overground or community ambulation which often require assistive devices such as a cane, walker, or crutches (Lee and Hidler, 2008). Even though the mean kinematic trajectories are similar between treadmill and overground walking, overground walking inherently requires greater step-to-step variability (Dingwell et al., 2001). Overground walking is a highly complex motor task that requires flexible motor control strategies that adapt muscle coordination to step-to-step variations in environmental and mechanical demands (Chvatal and Ting, 2012; Dingwell et al., 2001; Nielsen, 2003), especially compared to more controlled locomotor demands such as single-speed treadmill walking (Dingwell et al., 2001).

The complexity of neuromuscular control required for overground walking is deficient after iSCI, resulting in numerous walking deficits. For example, persons with iSCI present an inability to modulate walking speed outside a small range of slow speeds (Pepin et al., 2003), a dependence on assistive devices (van Hedel and Dietz, 2009), and a failure to adjust to environmental perturbations that subsequently lead to increased falls (Brotherton et al., 2007). The extent of these walking deficits vary widely with injury level, severity, and the pathways damaged, making it difficult to assess the underlying neuromuscular mechanisms (van Hedel and Dietz, 2010).

To date, it is unclear to what extent inappropriate muscle coordination contributes to overground walking deficits after chronic iSCI. Quantifying the contribution of altered muscle coordination is particularly challenging due in part to the large number of muscles that contribute to overground walking. Non-negative matrix factorization (NNMF) quantifies this complexity via extraction of motor modules, or groups of consistently co-activated muscles, that represent the "building blocks" of muscle coordination. Motor modules can be characterized in terms of number, composition (i.e., number of muscles per motor module), and activation (i.e., duration and amplitude). Motor modules can be flexibly activated in combination to produce a wide range of muscle coordination patterns during various motor tasks, with each module achieving a specific biomechanical outcome that subserves the overall biomechanical goal (Cappellini et al., 2006; Chvatal and Ting, 2012; Chvatal et al., 2011; d'Avella et al., 2011; Drew et al., 2008; Fox et al., 2013; Ivanenko et al., 2004; Neptune et al., 2009; Overduin et al., 2008; Torres-Oviedo et al., 2006). Motor modules also are useful in identifying constraints on muscle coordination related to gait deficits in neurologic pathologies such as stroke, spinal cord injury, and Parkinson's disease (Allen et al., 2013; Bowden et al., 2010; Cheung et al., 2009b; Clark et al., 2010; Fox et al., 2013; Rodriguez et al., 2013). Following hemiparetic stroke, as well as, Parkinson's disease, persons exhibit fewer motor modules during walking (Clark et al., 2010; Rodriguez et al., 2013). This reduction is closely related to limited walking speed and walking complexity. Similar findings have been made in pediatric spinal cord injury (Fox et al., 2013), but not explored in adult spinal cord injury. Additionally, most studies have focused on module number without extensive exploration of module composition or activation across the gait cycle.

Thus, the purpose of this study was to quantify neuromuscular deficits in muscle coordination during overground walking in persons with chronic iSCI. We hypothesized that overground muscle coordination is constrained by greater muscle co-activity in persons with iSCI as compared to age-matched (AB) controls. We predict that persons with iSCI have fewer motor modules, as well as, altered composition (i.e., increased number of muscles per motor module) and activation (i.e., increased duration) of motor modules as compared to AB controls. We examined motor modules from 14 muscles during a cadence-matched overground-walking task and revealed that changes in motor module number, composition, and activation contribute to deficits in overground walking after iSCI. Understanding the subject-specific neuromuscular constraints on muscle coordination is critical for effectively developing therapies that are more tailored to a heterogeneous population of persons with chronic iSCI and to the complexities of community ambulation.

2. Methods

2.1. Study population

Eight persons with iSCI (34.4 ± 3.8 years; mean ± 1 standard error) and eight age-matched AB controls (34.1 ± 4.1 years) participated in this study (Table 1). AB subjects also were selected to match gender and approximate body type. Ethical approval for the study was received from the Emory University Institutional Review Board (IRB protocol STU00044670); informed consent and HIPAA authorization were obtained from all subjects prior to their participation in accordance with the Declaration of Helsinki.

We included iSCI subjects with incomplete injuries to the spinal cord between levels C4 and T10 who were at least one year post injury (i.e., chronic), were able to walk overground at least 10 m with reciprocal pattern and without the assistance of another person, and were able to follow simple verbal, visual, and auditory commands. We excluded subjects if they had a brain injury as defined from chart review, progressive SCI, other concurrent medical condition, and/or history of contraindications to surface electromyography (EMG) such as adhesive allergy. We excluded AB participants if they had a concurrent medical condition and/or neurological impairments.

2.2. Clinical assessments

We recorded injury severity as well as lower extremity strength and mobility using a set of standard clinical tests. The American Spinal Injury Association Impairment Scale (AIS) was used to categorize subject neurological injury level and completeness. Strength was assessed using the Lower Extremity Motor Score (LEMS) from the AIS (Marino et al., 1999). The Spinal Cord Injury Functional Ambulation Inventory (SCI-FAI) was used to identify clinically observable gait deficits (Field-Fote et al., 2001), and the 10 m Walk Test identified the maximum walking speed (van Hedel et al., 2007). Walking tests were performed using the minimum assistive device possible for safe walking.

2.3. Equipment

We recorded surface EMGs from 14 muscles on the right leg (Fig. 1A), which included the tibialis anterior (TA), medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SO), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), medial hamstring (MH), lateral hamstring (LH), gluteus medius (GMED), gluteus maximus (GMAX), tensor fascia lata (TFL), sartorius (SART), and adductor magnus (ADDM). These muscles accounted for single