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Generalization of improved step length symmetry from treadmill to overground walking in persons with stroke and hemiparesis ☆

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HIGHLIGHTS

- Locomotor adaptation to a unilateral swing phase resistance during treadmill walking generalized to overground walking in all study participants.
- Overground aftereffects resulted in a temporary reduction of step length asymmetry in participants with stroke who had baseline step length asymmetry.
- Aftereffects in participants with stroke decayed at a slower rate overground compared to controls, despite no difference in the rate of treadmill adaptation between the two groups.

ABSTRACT

Objectives: Determine whether adaptation to a swing phase perturbation during gait transferred from treadmill to overground walking, the rate of overground deadaptation, and whether overground aftereffects improved step length asymmetry in persons with hemiparetic stroke and gait asymmetry.
Methods: Ten participants with stroke and hemiparesis and 10 controls walked overground on an instrumented gait mat, adapted gait to a swing phase perturbation on a treadmill, then walked overground on the gait mat again. Outcome measures, primary: overground step length symmetry, rates of treadmill step length symmetry adaptation and overground step length symmetry deadaptation; secondary: overground gait velocity, stride length, and stride cycle duration.
Results: Step length symmetry aftereffects generalized to overground walking and adapted at a similar rate on the treadmill in both groups. Aftereffects decayed at a slower rate overground in participants with stroke and temporarily improved overground step length asymmetry. Both groups' overground gait velocity increased post adaptation due to increased stride length and decreased stride duration.
Conclusions: Stroke and hemiparesis do not impair generalization of step length symmetry changes from adapted treadmill to overground walking, but prolong overground aftereffects.
Significance: Motor adaptation during treadmill walking may be an effective treatment for improving overground gait asymmetries post-stroke.

1. Introduction

Alterations in the normal pattern of walking often occur after stroke and addressing these walking deficits is a major focus of neurological rehabilitation. In individuals with post-stroke hemiparesis, gait is characterized by decreased speed and cadence along with other spatiotemporal changes that frequently lead to asymmetries of step length (Brandstater et al., 1983; von Schroeder et al., 1995; Hesse et al., 1999; De Bujanda et al., 2003). These deficits can result in an inefficient (e.g., requires increased energy to walk a given distance compared to non-disabled) and functionally

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less effective (e.g., unable to cross a street before a traffic light changes) gait pattern (Wall and Turnbull, 1986; Hsu et al., 2003; Chen et al., 2005; Balasubramanian et al., 2007; Oken and Yavuzer, 2008). Many interventions have been shown to improve some features of walking in persons with hemiparetic gait (Silver et al., 2000; Teixeira-Salmela et al., 2001; Peurala et al., 2005; Dunsky et al., 2008; Patterson et al., 2008; Regnaux et al., 2008), but they have generally shown little ability to alter gait asymmetries. Furthermore, although gait speed is an important rehabilitation goal (Schmid et al., 2007; Tilson et al., 2010), the relationship between gait speed and asymmetry is unclear.

Recently, we have shown that motor adaptation to a swing phase perturbation during treadmill walking can temporarily alter gait symmetry in nondisabled individuals (Savin et al., 2010) and those with stroke and hemiparesis (Savin et al., 2013). Motor adaptation is a practice-dependent alteration of an established movement pattern caused by a sensorimotor perturbation (Martin et al., 1996). It requires the cerebellum (Morton and Bastian, 2006) and produces aftereffects, i.e., movement errors that are opposite those seen during the initial adaptation. Aftereffects indicate that feedforward motor commands are updated and stored by the central nervous system (Weiner et al., 1983; Shadmehr and Mussa-Ivaldi, 1994) and can be thought of as evidence for short-term motor learning (Shadmehr and Wise, 2005). Evidence suggests that by perturbing hemiparetic gait so that baseline (pre-perturbed) asymmetry is initially increased, the resulting aftereffects can temporarily improve symmetry (Reisman et al., 2007, 2009, 2013; Savin et al., 2013). As such, locomotor adaptation (motor adaptation of gait) has been suggested as a potential treatment for the asymmetries of hemiparetic gait (Reisman et al., 2009).

To be an effective treatment for gait asymmetries, aftereffects resulting from locomotor adaptation during treadmill walking must generalize to overground walking. However, locomotor adaptation in animal models has been suggested to be context specific. For example, when cats adapt their gait on a treadmill, aftereffects are present during subsequent post-adaptation treadmill walking but not during overground walking (McVea and Pearson, 2007). However, in humans, evidence suggests that locomotor adaptation can generalize to a different context (Anstis, 1995; Weber et al., 1998; Earhart et al., 2002; Reisman et al., 2009, 2013; Torres-Oviedo and Bastian, 2010, 2012). Yet to our knowledge, only two studies have shown that locomotor adaptation generalizes from treadmill to overground walking in participants with stroke (Reisman et al., 2009, 2013) and none have investigated rates of overground deadaptation.

The rate at which motor adaptation occurs has been frequently studied (Martin et al., 1996; Smith et al., 2006; Wei and Körding, 2010; Savin et al., 2013) while the rate of deadaptation has not. We previously showed that the rate of initial fast (i.e., the first 10–30 strides) locomotor adaptation did not differ between controls and participants with stroke during treadmill walking (Savin et al., 2013). Therefore it would be reasonable to expect that the initial deadaptation rates in persons with stroke would be similar compared to nondisabled individuals. It is also unknown whether our specific adaptation paradigm, utilizing a swing phase resistance, can produce symmetric step lengths that will generalize to overground walking in persons with stroke and hemiparesis.

The primary purpose of this study was to test the extent to which locomotor adaptation to a swing phase perturbation during treadmill walking generalized to overground walking in participants with post-stroke hemiparesis and controls. We hypothesized that all participants would show a generalization of step length symmetry adaptation and that participants with stroke and controls would have similar rates of deadaptation overground. We also hypothesized that by perturbing the leg with the shorter overground step length in persons post-stroke, the resulting aftereffects would decrease overground step length asymmetry. The secondary purpose of this study was to investigate the effects of aftereffect-induced changes in step length symmetry on overground gait parameters (e.g., speed) in participants with stroke.

2. Methods

2.1. Participants

Ten participants with stroke and hemiparesis (7 female, aged 62.8 ± 9.4 years) and 10 age- (±5 years) and gender matched nondisabled controls (aged 61.8 ± 9.3 years) were recruited to participate in the study. All participants gave informed consent and the study protocol was approved by the joint Baltimore Veterans Administration and University of Maryland Baltimore Institutional Review Board. Participants with stroke were included if they had a history of unilateral ischemic stroke occurring >9 months earlier and were able to walk $\geqslant$0.4 m/s on a treadmill. Lesion location was determined by CT or MRI and classified by a neurologist as cortical, subcortical, and/or brainstem. Participants with stroke were excluded if they had a history of stroke affecting both hemispheres, cerebellar damage, other neurological or orthopedic conditions affecting the legs or a Mini Mental State Exam (Folstein et al., 1975) score <22. All participants with stroke walked without the use of an ankle–foot orthosis or assistive device see Table 1 for further details.

2.2. Testing paradigm

Participants undertook four consecutive testing conditions: *Overground Baseline*, *Treadmill Baseline*, *Treadmill Adaptation* and *Overground Generalization*. During overground conditions participants walked on a 7.9 meter-long GAITRite mat (CIR Systems, Inc., Sparta, NJ, USA). They were instructed to walk at their preferred speed with their arms free to swing. During treadmill conditions, participants walked on a motorized treadmill (Woodway, Inc., Waukesha, WI, USA). While walking on the treadmill, participants were instructed to hold onto the front hand rail, look straight ahead, avoid looking at their feet, and not think about their walking. For safety, all participants wore a harness to prevent falling. In all conditions, participants wore custom-made padded cuffs around each of their lower legs to which the perturbation device could be attached see Fig. 1A.

During *Overground Baseline* participants walked the length of the GAITRite mat three times. During treadmill walking, the treadmill's speed was set to 80% of a participant's overground gait speed to minimize any confounding effect on gait due to the perception that they were walking faster on the treadmill compared to overground (Dal et al., 2010). Details of the treadmill paradigm have been previously published (Savin et al., 2010). Briefly, participants walked on the treadmill during *Treadmill Baseline* and *Adaptation* conditions, lasting five and 10 min, respectively. During the *Treadmill Adaptation* condition, a rope was attached to the cuff on the leg having the shorter overground step length as determined by the GAITRite mat. The other end of the rope passed through a set of pulleys and was connected to a weight equal to 1.25% of the participant's body weight, rounded to the nearest 0.11 kg, which resisted forward movement of that leg during its swing phase see Fig. 1A. Following *Treadmill Adaptation*, participants were instructed to remain on the treadmill belt while a wheelchair was brought to them. The harness and weight were unhooked and participants sat in the wheelchair. They were then wheeled off the treadmill