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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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Abstract

Objectives—Determine whether adaptation to a swing phase perturbation during gait transferred from treadmill to overground walking, the rate of overground deadadaptation, 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 deadadaptation; 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.

Keywords

Gait; motor adaptation; CVA; motor learning

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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 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; Regnaud 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 deadadaptation.

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 deadadaptation 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 deadadaptation 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 deadadaptation 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 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). 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). 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 Figure 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 minutes 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 Figure 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 and positioned at the end of the GAITRite mat. During the *Overground Generalization* condition, participants walked the length of the mat five times, again at their preferred speed. See Figure 1B. When participants reached the end of the mat, they were instructed to walk off and stop without turning around. They were then seated in the wheelchair and turned around. In this manner, all strides during this condition occurred on the GAITRite mat.

2.3. Data Collection

Spatial and temporal gait parameters during overground walking were collected at 120 samples/s with the GAITRite system. Position data during treadmill walking were collected with two Optotrak Certus position sensors (NDI, Waterloo, Ontario, Canada), one on each side of the treadmill. We placed infrared emitting diodes over the head of the fifth metatarsal and the lateral malleolus bilaterally to define the foot and ankle positions. Position data were collected continuously at 100 samples/s during treadmill walking.

2.4. Data Analysis

Overground gait parameters were analyzed with GAITRite software. Treadmill position data were analyzed with custom written MATLAB (MathWorks, Natick, MA) software. Position data were low-pass filtered at 6 Hz. During treadmill walking, we identified each stride as the time from initial contact on one foot to the next initial contact on the same foot. Initial contact was identified as the time when the ankle marker reached its maximum forward position. Lift off was the time when the foot marker reached its maximum backward position (Noble and Prentice, 2006). Step length was defined as the forward distance between the two ankle markers at initial contact. Single limb support (SLS) time was defined as the time from lift off on one foot to the next initial contact on the same foot.

Primary outcome variables were step length symmetry, rate of step length symmetry adaptation on the treadmill, and rate of step length symmetry deadadaptation overground. Secondary outcome variables were overground gait velocity, overground SLS time symmetry (measured as a percentage of the stride cycle), variability of SLS time and step length symmetry (standard deviation), and stride length and stride cycle duration changes. Symmetry was quantified with a symmetry index: $SI = (X_u - X_p)/(X_u + X_p)$, where u is the unperturbed leg (e.g. the leg with the longer overground baseline step length, irrespective of side of paresis in the stroke group), p is the perturbed leg (Noble and Prentice, 2006), and X represents the variable of interest (i.e., step length or SLS time). Perfect symmetry will result in a symmetry index value of zero. Rates of step length symmetry adaptation and deadadaptation were calculated by first smoothing each participant's data using a moving average with a window width of 2 data points. To determine adaptation and deadadaptation rates, an exponential decay function was then fit to each participant's data (Lang and Bastian, 1999) with the form of $y = a + (b * e^{-t/c})$ where a is the final value that the exponential decay function approaches, i.e. the plateau reached at the end of adaptation/deadaptation, b is the magnitude of adaptation or deadadaptation required from the first trial value to the value a , t is the stride number and c is the decay constant or the rate at which adaptation or deadadaptation occurs. In our paradigm, c is the number of strides it will take to obtain $(1 - e^{-1})$ or approximately two thirds of the adaptation or deadadaptation (Lang and Bastian, 1999). In order to ensure a logical and reasonable fit, we broadly constrained a to vary between -0.25 and $+0.25$, b was set to equal the difference between the first and final

adaptation/deadaptation symmetry values on a participant by participant basis, and c to vary between 1 and 40.

2.5. Statistical Analysis

We compared step length symmetry across key testing periods by averaging the last 5 strides of baseline conditions (*Overground* and *Treadmill Late Baseline*) and the first and last 5 strides of *Treadmill Adaptation* and *Overground Generalization* conditions (*Early* and *Late Treadmill Adaptation*, and *Early* and *Late Overground Generalization* respectively). Secondly, we compared overground SLS time symmetry, variability of SLS time and step length symmetry, gait velocity, stride length and stride cycle duration by averaging the last 5 strides of *Overground Late Baseline*, *Overground Early* and *Late Adaptation* conditions. See Figure 1B. Statistical comparisons were completed using Statistica software (StatSoft, Tulsa, OK). Step length symmetry indices and all secondary variables were compared with a factorial ANOVA with factors group (control and participants with stroke) and testing period, with repeated measures on testing period. When an ANOVA yielded a significant result, post hoc analyses were performed using Tukey's honest significant difference test. Adaptation and deadaptation rates were compared with independent samples t-tests. The level of statistical significance for these variables was set at $p < 0.05$. Data are presented as mean \pm 1 SD.

3. Results

One participant with stroke (S2) was removed from all analyses because she complained of vertigo-like symptoms after the treadmill adaptation and required assistance to walk during the first overground generalization trial. There was no difference between subject groups with respect to age ($p = 0.81$). Average overground baseline and treadmill gait speeds for participants with stroke was 0.76 ± 0.3 and 0.61 ± 0.2 m/s, and for controls 1.24 ± 0.2 and 0.99 ± 0.2 m/s respectively. Average overground baseline step length asymmetry was greater for participants with stroke compared to controls (0.087 ± 0.062 versus 0.014 ± 0.013 , $p = 0.002$).

3.1. Perturbation-induced step length symmetry changes

Figure 2A shows individual step length symmetry changes during treadmill walking for a typical control and participant with stroke. When first perturbed in *Treadmill Adaptation*, symmetry index values showed an immediate increase (i.e. became more positive), indicating that the unperturbed leg had a longer step length than the perturbed. As walking continued, both participants' step symmetry index values were adjusted back toward baseline. Figure 2B shows group average step length symmetry changes during treadmill walking for controls and participants with stroke. The ANOVA had a main effect of testing period ($p < 0.0001$) but no group or interaction effects. Post hoc analysis indicated the perturbation caused step length symmetry indices to immediately increase in *Treadmill Early Adaptation* compared to *Late Baseline* (0.163 ± 0.15 vs. 0.046 ± 0.08 , $p < 0.001$). By *Treadmill Late Adaptation*, step length symmetry indices adjusted toward, but remained above baseline values (0.101 ± 0.09 vs. 0.046 ± 0.08 , $p < 0.05$).

Figure 3A shows stride-by-stride changes in overground step length symmetry for a typical control and participant with stroke. Note that aftereffects, present initially during *Generalization*, resulted in step length symmetry for the participant with stroke and asymmetry for the control participant. Figure 3B shows average overground step length symmetry changes for both groups. The ANOVA had main effects of group and testing period ($p < 0.01$ for both) but no interaction. Post hoc analysis on group showed symmetry indices for participants with stroke were more positive and therefore more asymmetrical

than controls (0.042 ± 0.07 vs. -0.002 ± 0.02 , $p < 0.01$). Post hoc analysis on testing period showed the perturbation resulted in a significant step length symmetry aftereffect (*Overground Late Baseline* to *Overground Early Generalization*, 0.044 ± 0.06 vs. -0.012 ± 0.04 , $p < 0.001$). Aftereffects resulted in participants with stroke as a group temporarily walking with step length symmetry overground. By *Overground Late Generalization*, step length symmetry indices returned to *Baseline* (0.025 ± 0.05 vs. 0.044 ± 0.05 , $p = 0.22$). See Table 2 for group average step length values for the perturbed and unperturbed legs across all experimental conditions.

3.2. Adaptation and deadadaptation rates

Figures 4A and 4B show group averaged step length symmetry treadmill adaptation and overground deadadaptation curves for controls and participants with stroke. Overground aftereffects for participants with stroke resulted in them initially walking with decreased step length asymmetry whereas controls walked with increased step length asymmetry. Note that while both groups appear to reach a plateau during treadmill adaptation, only the control group appears to reach a similar plateau during overground deadadaptation. Figures 4C and 4D show treadmill step length symmetry adaptation rates and overground step length symmetry deadadaptation rates for controls and participants with stroke respectively (goodness of fit for deadadaptation rates, average adjusted $r^2 = 0.25$ for participants with stroke and 0.59 for controls). There was no difference in adaptation rates during treadmill walking between participants with stroke and controls (12.1 ± 15.0 vs. 13.6 ± 15.2 strides). However there was a difference in overground deadadaptation rates. Participants with stroke required more strides to deadapt overground than controls (11.8 ± 6.7 vs. 6.2 ± 3.0 , $p < 0.05$). While controls took more steps during treadmill adaptation than participants with stroke (787 ± 131 versus 604 ± 128 , $p = 0.007$) and fewer steps during Overground Generalization (48 ± 7 versus 73 ± 21 , $p = 0.003$ independent samples t-test for both), we found no significant correlations between the number of steps taken during treadmill adaptation and overground deadadaptation rate ($R = -0.46$, $p = 0.21$ for controls and $R = -0.14$, $p = 0.71$ for participants with stroke, Spearman Rank Order correlation).

3.3. Secondary measures

Figure 5A shows group average overground gait speed changes. The ANOVA had main effects of group and testing period ($p < 0.01$ for both) but no interaction effect. Post hoc analysis on group indicated that participants with stroke walked slower overground than controls ($0.74 \pm 0.3\text{m/s}$ vs. $1.27 \pm 0.20\text{m/s}$, $p < 0.001$). Post hoc analysis on testing period indicated overground gait speed was slower during *Overground Early Generalization* and faster during *Overground Late Generalization* compared to *Overground Late Baseline* ($0.96 \pm 0.4\text{m/s}$ vs. $1.02 \pm 0.4\text{m/s}$, $p < 0.01$ and $1.08 \pm 0.4\text{m/s}$ vs. $1.02 \pm 0.4\text{m/s}$, $p < 0.02$ respectively). Figures 5B and 5C show group average overground stride length and stride cycle duration changes, respectively. Similar to overground gait speed, there were significant main effects of group and testing period for both ($p < 0.01$ for all), but no group by testing period interactions. For the group effects, as expected, the stroke group had decreased stride lengths and increased stride cycle durations compared to controls (post hocs, $p < 0.01$ for both). For the testing period effects, stride lengths were reduced during *Overground Early Generalization* compared to *Overground Late Baseline* (post hoc, $p < 0.05$) and increased during *Overground Late Generalization* compared to *Overground Late Baseline* (post hoc, $p < 0.01$). Stride cycle durations were reduced during *Overground Late Generalization* compared to *Overground Early Generalization* ($p < 0.01$). Overall, the secondary analyses of overground gait speed, stride length, and stride cycle duration all showed the typical changes expected post-stroke (slower speed, reduced stride length, and increased stride duration) as well as a relative slowing in *Overground Early Generalization*

with restoration of levels toward *Overground Late Baseline* by *Overground Late Generalization*.

There were no interactions or main effects for group or testing period for SLS time symmetry across overground conditions ($p = 0.26, 0.08$ and 0.18 respectively). (See Table 3 for group average SLS time values for each leg across overground conditions.) There were main effects for group for SLS time and step length symmetry variability, with stroke participants having greater variability than controls ($p = 0.02$ and 0.01 respectively). However there were no interactions or main effects for testing period for variability of SLS time symmetry ($p = 0.18$ and 0.10 respectively) or step length symmetry ($p = 0.75$ and 0.36 respectively) across overground testing conditions. Thus it did not appear that our swing phase perturbation altered overground SLS time or SLS time and step length variability.

4. Discussion

Our data supported our hypotheses that all participants would show a generalization of step length adaptation to overground walking and that overground aftereffects would temporarily decrease step length asymmetry in participants with stroke. Our data did not support our hypothesis that deadadaptation rates would be similar between participants with stroke and controls. Step length symmetry aftereffects in participants with stroke generalized to overground walking, demonstrating that despite stroke and hemiparesis, the motor system retained the capability to significantly alter its output through error-based learning mechanisms. This resulted in participants with stroke walking with step length symmetry, albeit temporarily, during the real world task of overground walking. This is significant for gait rehabilitation post-stroke given that these results occurred after only one 10-minute bout of treadmill walking, similar to those of Kahn and Hornby (2009) and Reisman et al., (2007, 2013), whereas traditional interventions lasting longer have not been able to alter gait symmetry (Silver et al., 2000; Peurala et al., 2005; Regnaud et al., 2008).

Overground step length symmetry deadadaptation rate differences could be due to several factors. The slower rate in persons with stroke could be reflective of their walking overground with greater step length symmetry immediately after treadmill adaptation, possibly representing a cost savings to the motor system since a symmetrical gait pattern could be more efficient and functional, e.g. allowing effective community ambulation, than an asymmetrical one (Wall and Turnbull, 1986; Hsu et al., 2003; Chen et al., 2005; Oken and Yavuzer, 2008; Hall et al., 2012; Finley et al., 2013). It is also possible that walking overground has a higher attentional demand for persons with stroke and this distraction interferes with deadadaptation. A previous study on split-belt treadmill adaptation in healthy adults found that distraction slows adaptation and subsequent deadadaptation rates but the effect of distraction during deadadaptation was not tested (Malone and Bastian, 2010). Evidence also suggests persons with stroke may have impairments integrating sensory information (Marigold et al., 2004; Lamontagne et al., 2007; Lamontagne and Fung, 2009; Lamontagne et al., 2010), which may increase sensory feedback variability, potentially decreasing deadadaptation rates (Wei and Körding, 2010). However, post hoc we found no correlation between step length symmetry variability during treadmill adaptation and deadadaptation rates, (Spearman Rank Order correlations, $R = -0.42, p = 0.21$ for controls, $R = 0.08, p = 0.83$ for participants with stroke). This finding agrees with the results of Torres-Oviedo and Bastian (2012) who found that variability during adaptation was positively related to the magnitude, but not the deadadaptation of the aftereffect.

Reisman et al., (2009) reported findings consistent with ours when they found no differences in adaptation but a greater transfer of split-belt treadmill adaptation to overground walking in persons with stroke compared to controls. They speculated that deficits in the ability of

participants with stroke to modify their motor plan in response to a contextual change (e.g. from walking on a split-belt treadmill to walking overground) could explain the greater transfer magnitude. Anecdotally, we used the methods described in this study to re-analyze data from a previous study (Savin et al., 2013) involving controls and persons with stroke adapting and de-adapting their gait to our swing phase perturbation during treadmill walking. We found no group differences in deadadaptation rates *on the treadmill*. Additionally, when comparing treadmill and overground deadadaptation rates within groups, controls deadadapted significantly faster overground than on the treadmill while there were no differences in rates for participants with stroke. While somewhat speculative, taken together these further suggest that persons with stroke have impairments in modifying their gait pattern when the walking context changes (e.g. from treadmill to overground). Regardless of the mechanisms, this impairment in locomotor deadadaptation rate overground may have the potential to be beneficial in gait rehabilitation, since it allowed participants with stroke to walk with step length symmetry changes for a longer time than controls. Further study will be needed to determine whether this can be used advantageously in the rehabilitation of asymmetrical gait.

We found no significant group by testing period interaction effects in our secondary outcome measures. Thus for these measures, participants with stroke behaved like nondisabled controls. It is interesting to note that while all participants walked slower in the *Overground Early Generalization* condition compared to *Overground Late Baseline*, they walked faster in *Overground Late Generalization*. It is perhaps not surprising that gait speed was slower in the *Overground Early Generalization* condition given that we set the treadmill speed to 80% of baseline overground gait speed.

While asymmetry often results in decreased gait function and efficiency (Wall and Turnbull 1986; Chen et al. 2005; Hsu et al. 2003; Oken and Yavuzer 2008), step length symmetry may not be as important to gait speed as is sometimes thought (c.f. Latash and Anson, 1996). Indeed, the rehabilitation goal of a symmetrical gait pattern is somewhat controversial since with asymmetrical constraints an asymmetrical gait may be more functionally effective. For our participants with stroke, the return to asymmetry with accompanying speed increases from early to late generalization could be an indication of gait becoming more comfortable. For nondisabled it may also be an indication of gait becoming more comfortable as they return to symmetry. In other words, both groups return to their respective, well-practiced baseline gait patterns while increasing their preferred overground speed. In sum, improving asymmetry was not actually detrimental to gait speed for individuals with stroke and returning to asymmetry was beneficial.

5. Study Limitations

One study limitation was that participants with stroke were mildly impaired based on their lower extremity Fugl-Myer assessment scores, possibly decreasing our ability to generalize our findings to stroke survivors as a whole. Another limitation is that differences in gait speed between controls and participants with stroke resulted in controls taking more strides during adaptation than participants with stroke. Thus controls were exposed to the perturbation for a greater number of stride cycles. While this could have resulted in differences in aftereffects and deadadaptation rates between groups, we do not believe this to be the case. First there was no group by testing period interaction in treadmill step length symmetry, indicating both groups responded similarly. Second, both groups had significant aftereffects overground. If anything, we would have expected participants with stroke, who on the whole took fewer steps during adaptation, to have had less robust aftereffects, which our data do not support.

6. Conclusions

In summary, we have shown that adaptation to our swing phase perturbation during treadmill walking generalizes to overground walking in controls and persons with stroke and individuals with post-stroke hemiparesis retain the ability to alter gait symmetry in the real-world task of overground walking. Locomotor adaptation to a swing phase perturbation during treadmill walking appears to have the potential to be an effective and low-cost means of bringing about short-term improvements in overground step length symmetry. Decreased rates of deadadaptation in persons post-stroke allowed them to walk with gait symmetry for a longer time. This may prove beneficial if this paradigm is used to improve hemiparetic gait asymmetry since it allows more time on the task of walking with gait symmetry. Further study is needed to determine whether aftereffect-driven symmetry can be made more durable and whether improved asymmetry also results in improvements in functional gait.

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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.
- After effects 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.

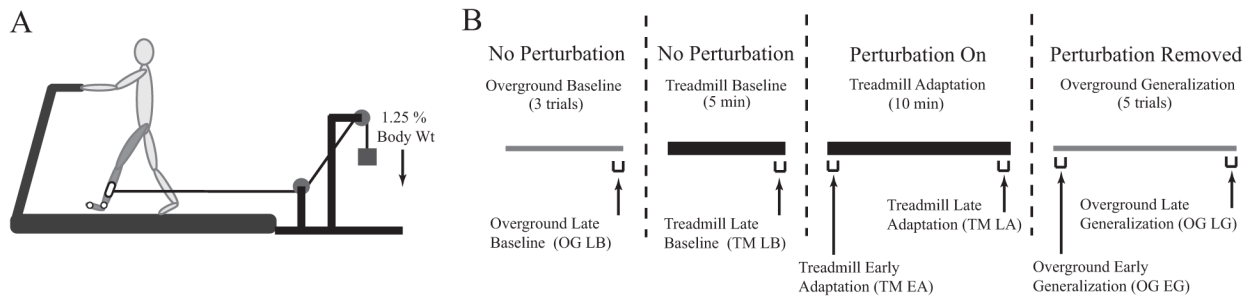


Figure 1.

A. Illustration of the treadmill setup. The small circles represent position marker placement. The weight and pulley system was positioned directly behind the perturbed leg. B. Time course of the experiment showing conditions and key testing periods.

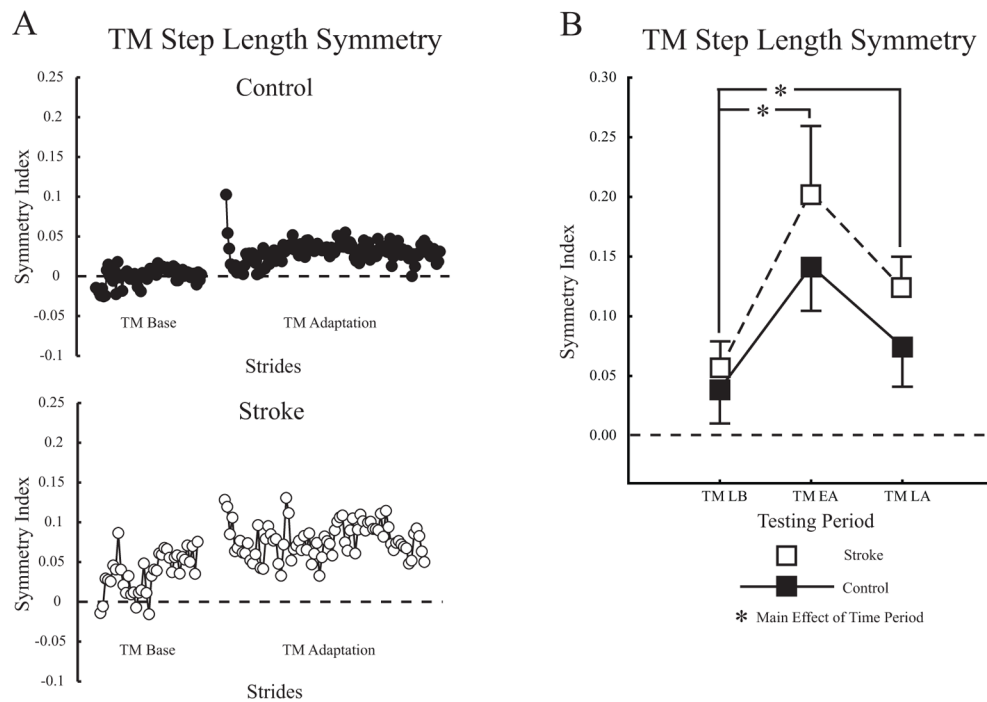


Figure 2.

A. Step length symmetry during treadmill walking plotted on a stride-by-stride basis for a typical control and participant with stroke. Each circle represents the average of three consecutive strides. B. Group average step length symmetry changes across treadmill conditions for all participants. *Treadmill Late Baseline (TM LB)*, *Treadmill Early Adaptation (TM EA)*, *Treadmill Late Adaptation (TM LA)*. The dashed horizontal line in all plots indicates perfect symmetry. Asterisks indicate significance level of $p < 0.05$ from post hoc analyses of each condition vs. late baseline for the main effect of testing period. Error bars ± 1 SEM.

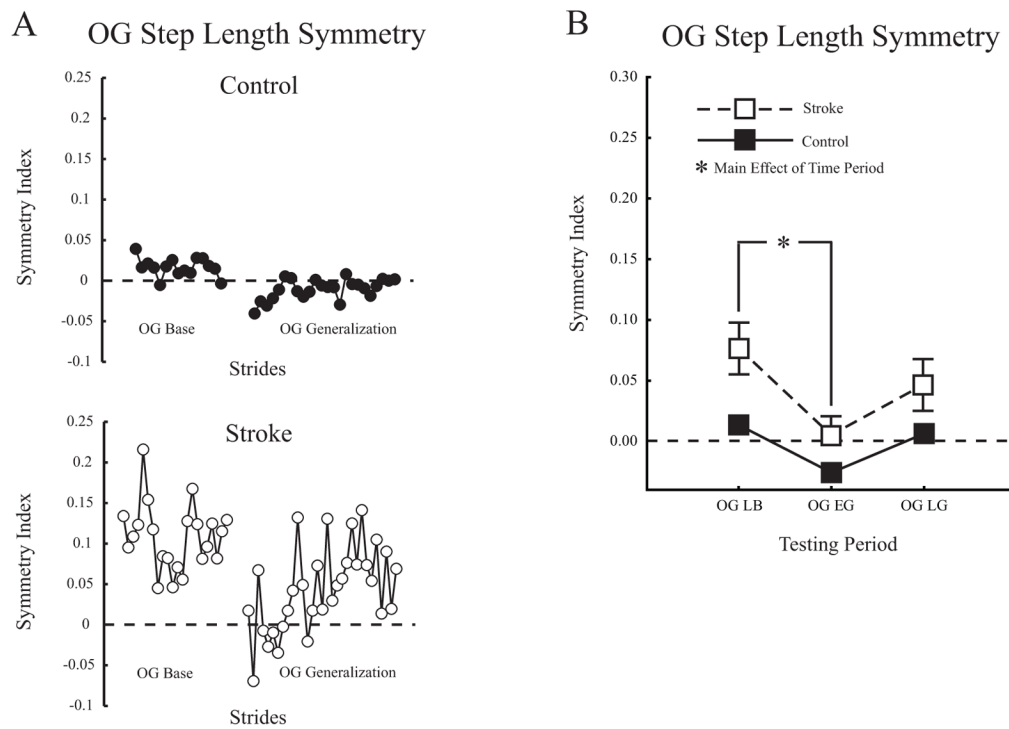
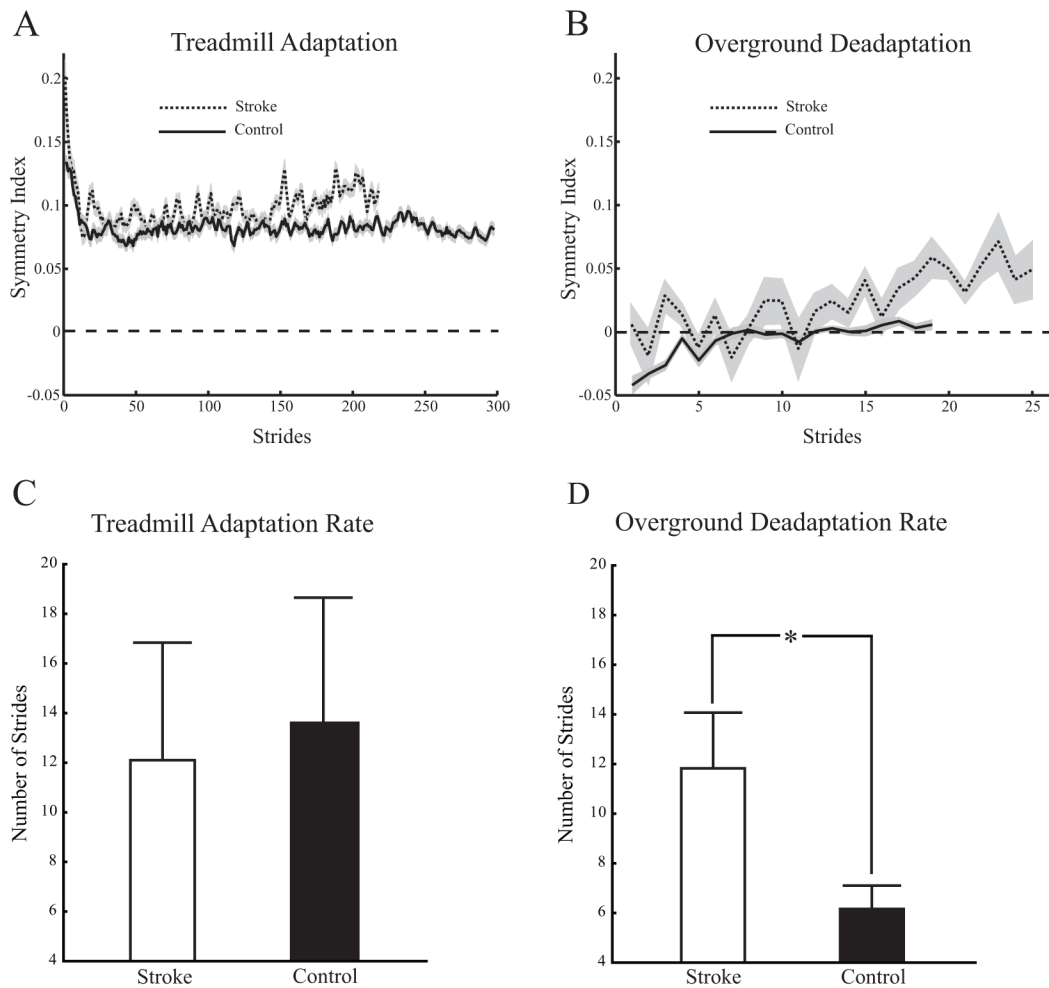


Figure 3.

A. Step length symmetry during overground walking plotted on a stride-by-stride basis (not averaged) for a typical control and participant with stroke. B. Group average step length symmetry changes in overground walking. *Overground Late Baseline (OG LB)*, *Overground Early Generalization (OG EG)*, *Overground Late Generalization (OG LG)*. The dashed horizontal lines indicate perfect symmetry. Asterisk indicates significance level of $p < 0.05$ from post hoc analyses of each condition vs. late baseline for the main effect of testing period. Error bars ± 1 SEM.

Group Average Step Length Symmetry

**Figure 4.**

A and B. Group average treadmill and overground step length symmetry adaptation and deadaptation plots for controls and participants with stroke. Dashed lines indicate perfect symmetry. Solid lines represent the control group; dotted lines represent the stroke group. Gray shading indicates ± 1 SD. C. Treadmill adaptation rates for control participants and those with stroke. D. Overground deadaptation rates for control participants and those with stroke. Asterisk indicates significance level of $p < 0.05$. Error bars ± 1 SEM.

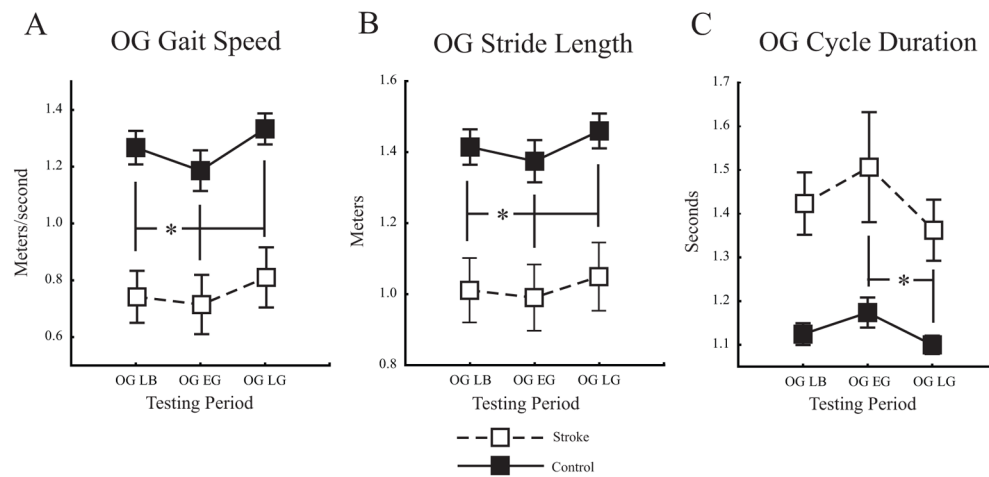


Figure 5.

A. Group average overground gait velocity. B. Group average overground stride length. C. Group average overground stride cycle duration. *Overground Late Baseline (OG LB)*, *Overground Early Generalization (OG EG)*, *Overground Late Generalization (OG LG)*. Asterisks for A and B indicate significance level of $p < 0.05$ from post hoc analyses of each condition vs. *Overground Late Baseline* for the main effect of testing period. Asterisk in C indicates significance level of $p < 0.05$ from post hoc analysis of *Early vs. Late Overground Generalization* for the main effect of testing period. Error bars ± 1 SEM.

Table 1

Demographics of participants with stroke.

Participant	Age	Gender	Time Since Onset	Lesion Information
S1	63	F	7.5 y	Subcortical, internal capsule
S2	67	F	48.8 y	Cortical
S3	69	M	9.8 y	MCA infarct, cortex + subcortical
S4	60	F	2.3 y	Cortical
S5	54	M	7.4 y	Cortical
S6	76	F	9.5 y	Brainstem
S7	56	F	6.8 y	Subcortical
S8	77	M	13.8 y	Subcortical, internal capsule
S9	57	F	4.8 y	Cortical
S10	49	F	4.8 y	MCA infarct, cortical
Mean	62.8(9.4)		11.6(13.5) y	

Abbreviations: MCA = middle cerebral artery; LE = lower extremity. Means \pm 1SD.

Table 2

Group average step length for perturbed and unperturbed legs across all experimental conditions.

Leg	OG LB	TM LB	TMEA	TM LA	OG EG
Step Length (cm) Stroke	Perturbed 45.9 (15.1)	38.6 (9.1)	32.8 (12.6)	36.3 (10.1)	48.2 (13.6)
	Unperturbed 53.0 (11.4)	42.2 (7.6)	45.9 (7.3)	45.1 (8.0)	48.1 (14.9)
Step Length (cm) Control	Perturbed 67.8 (9.4)	50.5 (6.6)	44.6 (9.0)	49.0 (8.1)	68.9 (10.0)
	Unperturbed 69.9 (8.4)	54.5 (5.9)	58.6 (5.3)	56.5 (5.4)	66.5 (9.3)

Abbreviations: OG LB = Overground Late Baseline, TM LB = Treadmill Late Baseline, TM EA = Treadmill Early Adaptation, TM LA = Treadmill Late Adaptation, OG EG = Overground Early Generalization, OG LG = Overground Late Generalization. Data presented as means \pm 1SD.

Table 3

Group average single limb support (SLS) time as a percent of the stride cycle across overground conditions.

	Leg	OG LB	OG EG	OG LG
SLS Time Stroke	Perturbed	33.9 (4.8)	33.7 (4.9)	33.8 (4.9)
	Unperturbed	29.1 (6.2)	27.8 (8.0)	29.9 (6.2)
SLS Time Control	Perturbed	37.0 (1.8)	36.9 (3.0)	37.4 (1.5)
	Unperturbed	36.0 (2.6)	35.7 (2.5)	36.7 (2.1)

Abbreviations: OG LB = Overground Late Baseline, OG EG = Overground Early Generalization, OG LG = Overground Late Generalization. Data presented as means \pm 1SD.