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SPLIT-BELT TREADMILL TRAINING POST-STROKE: A CASE STUDY

Darcy S. Reisman[1,2], **Heather McLean**[2], and **Amy J. Bastian**[2,3,4]

[1]Department of Physical Therapy, University of Delaware, Newark, Delaware 19716

[2]Kennedy Krieger Institute, Johns Hopkins University School of Medicine, Baltimore, Maryland 21205

[3]Department of Neurology, Johns Hopkins University School of Medicine, Baltimore, Maryland 21205

[4]Department of Physical Medicine and Rehabilitation, Johns Hopkins University School of Medicine, Baltimore, Maryland 21205

Abstract

Background/Purpose—Even after rehabilitation, many individuals with stroke have residual gait deviations and limitations in functional walking. Applying the principles of motor adaptation through a split-belt treadmill walking paradigm can lead to short-term improvements in step length asymmetry after stroke. The focus of this case study was to determine whether it is possible to capitalize on these improvements for long-term gain.

Case Description—The participant was a 36-year-old female who was 1.6 years post-stroke. She had a slow walking speed and multiple specific gait deviations, including step length asymmetry.

Intervention—The participant walked on the split-belt treadmill 3 days/week for four weeks, with the paretic leg on slow belt. The goal was 30 minutes of split-belt treadmill walking each day, followed by overground walking practice to reinforce improvements in step length symmetry.

Outcome—With training, step length asymmetry decreased from 21% to 9%, and decreased further to 7% asymmetry 1 month after training. Self-selected walking speed increased from 0.71 m/s to 0.81 m/s after training and 0.86 m/s 1 month later. Percent recovery, measured by the Stroke Impact Scale, increased from 40% to 50% post-training and to 60% 1 month later.

Discussion—Improvements in step length symmetry were observed following training and these improvements were maintained 1 month later. Concomitant changes in clinical measures were also observed, although these were relatively modest. The outcomes for this participant are encouraging given the relatively small dose of training. They suggest that short-term adaptation can be capitalized on through repetitive practice and can lead to longer-term improvements after stroke.

BACKGROUND AND PURPOSE

According to the World Health Organization, 15 million people worldwide suffer a stroke each year. One of the primary concerns for individuals who experience stroke is the ability to regain walking function.[1] Consequently, significant effort is focused on gait retraining

Corresponding author: Darcy S. Reisman, Ph.D., P.T., University of Delaware, Dept of Physical Therapy, 322 McKinly Laboratory, Newark, DE 19716, PH: 302-831-0508, FAX: 302-831-4234, dreisman@udel.edu.

during rehabilitation following a stroke[2] and efforts to develop and improve locomotor retraining programs are a major focus of rehabilitation research. Despite these efforts, many individuals with stroke have residual gait deficits[3–8] and never achieve community ambulation status.[9, 10] Spatiotemporal gait asymmetries are prevalent after stroke and are related to slow walking speed.[6, 11, 12] Step length asymmetry also has consequences relative to other gait deviations. Specifically, a shorter non-paretic step length is related to a decreased propulsive force on the paretic leg,[3] which limits forward propulsion of the body, is related to slow gait speed,[3] and may be related to reduced efficiency.[13] Thus, recent post-stroke gait retraining interventions have targeted step length asymmetry to promote greater recovery of walking.[14]

Many novel rehabilitation interventions for those with stroke have emerged in the past several years.[14–16] Recently, a group of studies utilizing the principles of motor adaptation applied to walking have gained interest in the rehabilitation community because of their unique ability to target specific gait deviations.[17–20] In these studies, motor adaptation has a specific definition: it is the process of modifying or adjusting a movement from trial-to-trial based on error feedback[21] such that a new movement pattern is temporarily learned to respond to new task demands. Once the adaptation is complete, if the new demand is removed, movements are once again erroneous, this time in the opposite manner, because the adapted pattern remains. These initial, oppositely directed errors are termed after-effects. With continued practice with the demands removed, the movement pattern returns to baseline, again by modifying or adjusting the movement from trial-to-trial based on error feedback. Using this definition, then, motor adaptation is one specific component of true motor skill learning. To fully learn a novel motor skill (i.e., retain permanently) requires much longer time periods; the process is influenced not only by adaptive mechanisms, but also by offline learning, consolidation, and long-term storage.[22, 23]

Recent studies in persons post-stroke have shown that applying the principles of motor adaptation through a split-belt treadmill walking paradigm can lead to short-term improvements in step length asymmetry.[19, 20] In order to obtain these improvements, a person’s step length asymmetry must be exaggerated while walking on the split-belt treadmill. Specifically, a person with stroke who takes a longer step with the paretic leg and a shorter step with the non-paretic leg during regular walking would need to walk on the split-belt treadmill with the paretic leg on the slow belt. Initially this will cause the person to take an even longer step with the paretic leg and an even shorter step with the non-paretic leg. Over time (less than 15 minutes), the person will correct the exaggerated asymmetry by lengthening the non-paretic leg step and shortening the paretic leg step. When the belts are returned to the same speed, the person will continue this adjusted pattern, resulting in improved step length symmetry.[19, 20] The improvements in asymmetry are short-lived, and the person with stroke returns to the baseline asymmetry after several minutes of overground or treadmill walking. However, these results demonstrate that persons post-stroke retain the capacity to produce a more symmetric walking pattern, which could be capitalized on during rehabilitation.

A critical component of the split-belt treadmill studies described above is the strategy employed to achieve an after-effect of improved symmetry. Specifically, the participants step length asymmetry is exaggerated with the split-belt treadmill, thereby augmenting their “error” (asymmetry) during split-belt walking. This error augmentation is critical because it provides the nervous system with a cue to correct the asymmetry.[19, 20] This suggests an interesting and important concept for rehabilitation -- movement error augmentation may prompt the nervous system to make a movement correction. This could be especially useful for persons with chronic movement deviations, where the deviation may no longer be perceived by the nervous system as a movement error that requires correction.[18] This would suggest that rather than providing interventions that correct movement errors, it may be useful to enhance error and allow the individual to correct the movement.

The temporary improvements in step length and double support asymmetry observed in persons with stroke following split-belt treadmill adaptation occur on the treadmill and also transfer to overground walking.[19, 20] Thus, repetitive practice of the improved walking pattern following split-belt treadmill adaptation can be undertaken over ground, providing for optimal locomotor task-specific training. This makes the utility of this type of locomotor adaptation training particularly appealing for rehabilitation. However, in order to determine the potential value of split-belt locomotor adaptation in rehabilitation, it is important to know whether the short-term improvements observed can be translated into longer-term improvements through repetitive training. Thus, the purpose of this case study was to provide repetitive split-belt treadmill training in a person with stroke to determine whether longer-term changes in step length asymmetry and gait function could be achieved.

PARTICIPANT

The participant in this case study was a 36-year-old female who sustained a single hemorrhagic stroke, of undetermined etiology, involving the right insular region one year and seven months prior to training. Her other past medical history was unremarkable. She gave informed consent to participate in training based on procedures approved by the Human Subjects Review Board at the John Hopkins School of Medicine.

Following surgery and acute management, the participant received inpatient and outpatient rehabilitation, which ended several months prior to the start of this training intervention. Prior to her stroke, the participant was a full-time doctoral student. At the time of the training, she was continuing part-time with her studies and was not currently undergoing formal therapy. Her exercise activity was inconsistent and included walking on the treadmill and over ground outside when the weather permitted. She was independent in all activities of daily living and reported no history of falls in the past year. Observational analysis revealed that the participant walked without orthotic or assistive device, but with a slow walking speed for someone of her age. One the paretic side, stance time was noticeably shortened and step length was longer. She had difficulty clearing the ground with her paretic foot, and used compensatory patterns such as hip elevation and circumduction. She reported that fatigue limited her walking and the consistency of her exercise routine. The participant's goal from this intervention was to improve her walking quality, speed, and endurance.

BASELINE EXAMINATION

Clinical Evaluation

A detailed baseline clinical assessment was performed before the start of training. The participant had no major cognitive deficits or symptoms of hemispatial neglect as determined by the star cancellation test.[24] Self-selected walking speed was measured as the average of 3 trials along a 6-meter walkway, and fast walking speed was measured as the fastest of the 3 trials. The Timed Up and Go (TUG) test, lower extremity Fugl-Meyer, and Stroke Impact Scale (SIS) were administered using customary procedures.[25–27] Self-selected and fast walking speed, TUG test, lower extremity Fugl-Meyer, and SIS were repeated immediately following the completion of training and then again one month later. The participant's scores on these clinical tests are shown in Table 1.

Gait Analysis

Baseline overground walking characteristics of the participant were measured with computerized gait analysis using OPTOTRAK (Northern Digital, Waterloo ON) sensors that recorded 3-dimensional position data at 100 Hz from both sides of the body. Infrared emitting diodes (IREDs) were placed bilaterally on the foot (5^{th} metatarsal head), ankle (lateral malleolus), knee (lateral joint space), hip (greater trochanter), pelvis (iliac crest) and shoulder (acromion process). The participant walked over ground down a 9-meter walkway at her self-selected gait speed. Data from 7–8 trials were recorded and the middle two strides from each trial were used for analysis. Step length was calculated as the anterior-posterior distance between the ankle markers at the time when each foot contacted the ground. Step length was labeled paretic or non-paretic based on the leading leg. The percent time in double limb support was the time that both feet were in contact with the floor, expressed as a percentage of the stride time for each leg. The stance time (the time from foot contact to lift-off) was also expressed as a percentage of the stride time. Data from instrumented gait analysis in persons with chronic stroke has shown high day-to day-reliability (ICC's of 0.97–0.99) for spatiotemporal measurements during overground walking.[28] Furthermore, step length data collected from 3 persons post-stroke during overground walking with the motion capture system used in this study found day-to-day changes of no greater than 0.7 cm. As shown in Figure 1, the participant demonstrated a 10 cm step length asymmetry at baseline, with the paretic leg taking a longer step compared to the non-paretic leg. Given her substantial step length asymmetry, we configured the split-belt treadmill belt speeds during training to target step length asymmetry (see training protocol below).

INTERVENTION

The participant trained 3 days/week for four weeks. Each session lasted approximately 1 hour, including a warm-up on the treadmill and rest periods between bouts. The training was designed so the participant would walk on the split-belt treadmill in six 5-minute bouts for a total of 30 minutes of split-belt treadmill walking each day. However, for the first session of training, the participant completed only 4 bouts and for the second and third sessions, she completed only 5 bouts due to fatigue. For all subsequent sessions, she was able to complete all 6 bouts. During each training block, heart rate and the Rating of Perceived exertion (RPE)[29] were recorded at 2 and 4 minutes. If RPE exceeded 15 or heart rate exceeded 80% of age-predicted heart rate maximum, the participant was given a rest break. During the rest period heart rate and blood pressure were monitored.

During split-belt treadmill training, the participant walked with the paretic leg on the slow belt and the non-paretic leg on the fast belt. This leg-belt speed configuration was chosen so that the participant's baseline step length asymmetry would be exaggerated by the split-belts (initially, the leg on the slow belt takes a longer step than the leg on the fast belt, thus exaggerating the participant's asymmetry). The speed of the fast belt was close to the participant's fast overground walking speed (1.0 m/s) and the slow belt speed was half of the fast belt speed (0.5 m/s). During all treadmill walking the participant wore a ceiling-mounted harness for safety. The harness did not support body weight or interfere with participant's walking. The participant was allowed to use the front handrail of the treadmill for safety, but was encouraged not to use this support. By session 6, the participant could consistently walk on the treadmill without using the handrail. Each day, following completion of all treadmill walking bouts, the participant practiced walking over ground for approximately 5 minutes with verbal cueing from the physical therapist to reinforce the improved step length symmetry.

All evaluations were completed by a physical therapist with over 17 years of clinical experience (DSR) and all intervention sessions were completed by a different physical therapist with 19 years of experience (HM).

OUTCOMES

The clinical evaluation and gait analysis performed at baseline were repeated within one week of the end of training, and then again 1 month following the end of training.

Clinical Assessment

The outcomes from the clinical assessment are presented in Table 1. Self-selected walking speed increased from 0.71 to 0.81 m/s after-training and continued to improve slightly to 0.86 m/s 1 month later. Fast walking speed increased from 1.13 m/s to 1.2 m/s following training and this was maintained at the 1 month follow up. The time taken to complete the TUG test decreased from 11.62 to 10.21 seconds after training, and decreased further to 8.85 seconds 1 month later. On the participation domain of the SIS, scores declined slightly post-training, but then increased at 1 month post-training. Percent recovery as measured by the SIS increased by 10% at post-training, and increased an additional 10% 1 month later. The lower extremity portion of the Fugl-Meyer scale increased by two points at post-training and this increase was maintained 1 month later.

Gait Analysis

The outcomes for step length are illustrated in Figure 1. The step length on both legs increased from baseline to post-training and this gain was maintained at one month follow-up. Most importantly, however, step length asymmetry, which was the gait deficit targeted by the intervention, improved from 21% asymmetry at baseline to 9% asymmetry post-training, and improved further to 7% asymmetry by 1 month after training. The actual step length difference decreased from a 9.3 cm difference at baseline to a 4.5 cm difference post-training, and then a 3.7 cm difference one month later. Stance and double support time asymmetries, which were not targeted by the intervention, remained essentially unchanged (Table 2).

DISCUSSION

This case study examined whether short-term improvements in step length asymmetry following split-belt treadmill walking can be translated into longer-term improvements through repetitive training in a person with stroke. Improvements in step length asymmetry were observed following training and these improvements were maintained 1 month later. Concomitant changes in clinical measures were also observed, although in some cases these changes were relatively small. Nonetheless, the outcomes for this participant are encouraging, especially given the relatively small dose of training utilized.

Step length asymmetry is a pervasive gait deviation observed after stroke.[8, 11, 12] It is related to other gait deviations, such as decreased paretic leg propulsive force[11] and to slow self-selected walking speed.[11] The participant in this case study demonstrated an improvement of more than 50% in her step length asymmetry following split-belt treadmill training. Her actual step length difference decreased from almost 10 cm to less than 5 cm following training. This means that her step length asymmetry as a percentage of her paretic step length decreased from 21% to only 9%. Data from our lab has consistently shown that the average ± one standard deviation step length asymmetry in neurologically intact persons is around 5 cm,[19, 20, 30] and that step length asymmetry as a percentage of step length is approximately 2%. Thus, this participant with stroke now demonstrates a step length asymmetry that is closer to the normal range observed for neurologically intact persons. In addition, the improvement in step length asymmetry was achieved by an increase in step length on both legs, but with a relatively greater increase on the non-paretic leg. This is important because an improvement in asymmetry could also be achieved by a *decrease* in paretic leg step length. That type of change in asymmetry would not be as functionally desirable given that increased step length has been associated with increased walking speed following a treadmill and overground walking program in persons post-stroke.[31]

Step length asymmetry is relatively resistant to change with gait interventions after stroke[15, 32] (although see Kahn and Hornby, 2009).[14] One of the differences between the intervention in this case study and previous studies is the incorporation of error augmentation. During split-belt treadmill walking, the enhancement of the participant's asymmetry lead to trial-and-error adjustment of step length and to the symmetric after-effect observed. Trial-and-error practice has been shown to be important for human motor learning[33] and thus, may have been the mechanism underlying the improvements observed here.

Small improvements in the participant's walking speed were also observed following split-belt treadmill training. However, this change did not exceed the minimal detectable change (MDC) in self-selected walking speed for persons with chronic stroke.[34]

The time required by the participant to complete the TUG improved immediately following split-belt treadmill training, and showed continued improvement when tested 1 month later. The change of 2.77 seconds on the TUG exceeds the average change in TUG scores following overground gait training in persons post-stroke (1.81 seconds (95% CI=−2.29 to −1.33)),[36] but does not exceed the MDC previously reported for persons with chronic stroke.[34]

The participant also reported an improvement in her recovery from stroke and an increase in participation (both measured by the SIS). The 10-point change in participation from baseline to 1 month follow-up for our participant is much larger than the approximately 2-point change observed in a previous study.[38] A ten- to fifteen-point change in a single domain of the SIS has been suggested to represent real and meaningful change.[37] Also, important for the participant, is that her perception of her recovery from the stroke increased from 40% at baseline to 50% following the intervention, and then to 60% 1 month later.

It is noteworthy that the participant's perception of her recovery, her self-selected walking speed, and her time on the TUG all improved steadily from baseline to post-training to one month follow-up. Why did these measures continue to improve 1 month following the end of training? It is possible that the improvements in step length symmetry and walking speed observed following training allowed for greater ease of walking and greater walking practice, ultimately resulting in the continued improvement observed 1 month after training. Previous studies have shown that better step length symmetry is associated with faster walking speed,[11] and that increases in walking speed are accompanied by decreased energy expenditure and increased daily step activity in persons post-stroke.[39, 40] Unfortunately, we did not measure energy expenditure or daily step activity, which would have been useful information.

LIMITATIONS

There are several limitations to this case study. First, the participant experienced the testing protocol on multiple occasions, and therefore changes could have been due to experience and/or practice. Second, the changes observed could have been due to natural recovery, though this seems unlikely given that she was more than 1.5 years post-stroke at the time of testing. Third, the physical therapist performing the evaluations was not blinded to the intervention. Finally, it is possible that the improvement in step length asymmetry was due solely to the overground walking training and had nothing to do with the split-belt treadmill training. However, 33% of community-dwelling persons living with chronic stroke (including this participant) continue to demonstrate persistent asymmetries following participation in conventional physical therapy, of which over ground locomotor training is a common component.[8] Furthermore, other more conventional treadmill training studies that have also included an overground walking component have not found changes in step length asymmetry in persons post-stroke[41]. Thus, it seems unlikely that the overground walking component of the intervention alone (without the split-belt training prior to overground walking practice) accounted for the changes observed. However, a case study design does not allow us to rule out this possibility.

CONCLUSIONS

Previous single-session studies have suggested that rehabilitation interventions that utilize motor adaptation may be effective at targeting specific movement deficits after stroke.[19, 20, 42] This case study is the first report demonstrating that, through repetitive practice, it is possible to capitalize on the short-term adaptations observed in previous studies and obtain longer-term improvements. Specifically, improvements were observed in the participant's step length asymmetry (the gait deviation targeted by the intervention), and these improvements were maintained one month later. Changes in walking speed, time on the Timed Up and Go test, social participation, and her perception of recovery from the stroke all showed more modest improvements; the impact of the intervention on these variables is not clear. Current studies are underway to determine whether similar improvements are observed across a larger group of individuals with stroke, and to determine baseline characteristics that influence a person's response to this intervention after stroke.

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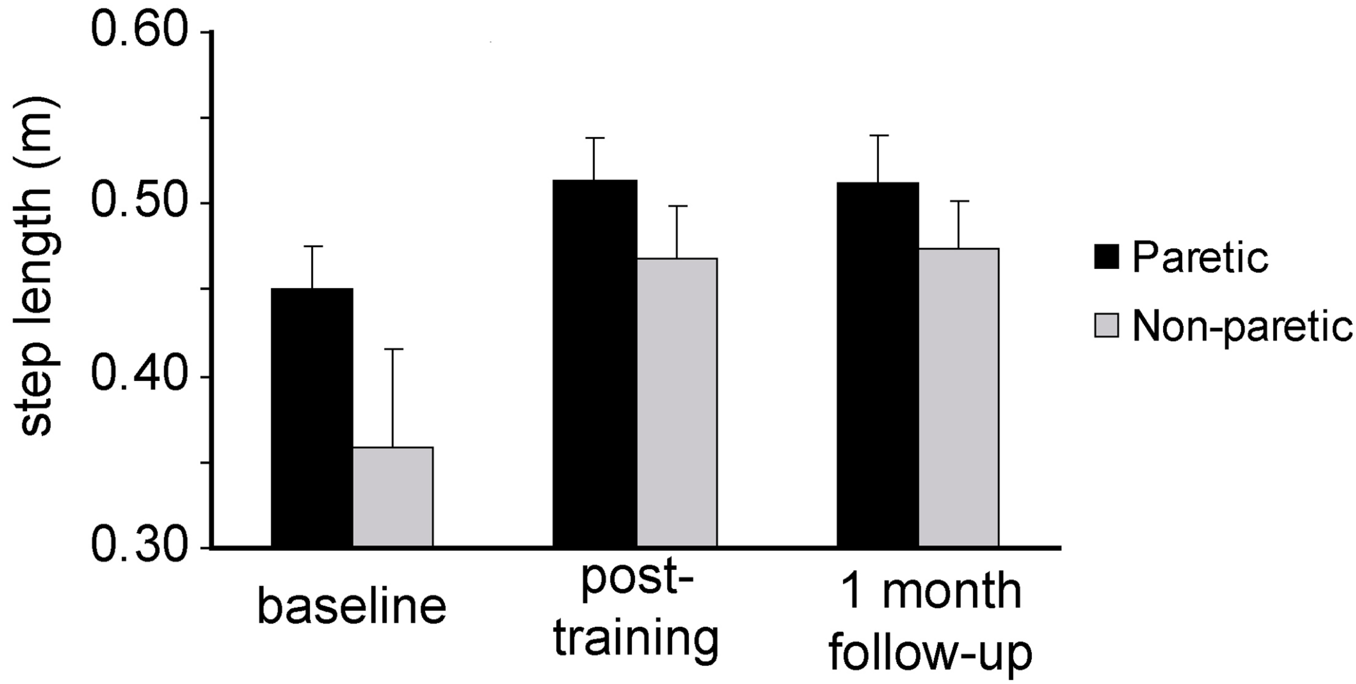

Figure 1.
Step length (in meters) during overground walking for the paretic (black bars) and non-paretic (grey bars) leg at baseline, post-training, and at follow-up 1 month later. Each bar represents the average step length over strides and error bars represent the standard deviation of the step length over strides.

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Table 1

Clinical outcome measures

	Pre-training	Post-training	1 month follow-up
Self-selected walking speed *(m/s)*	0.71	0.81	0.86
Fast walking speed *(m/s)*	1.13	1.2	1.2
Timed Up and Go (*sec*)	11.62	10.21	8.85
Stroke Impact Scale			
participation	59	56	69
% recovery	40%	50%	60%
Fugl-Meyer (Lower extremity)	24/34	26/34	26/34

Table 2

Temporal gait measures

	Pre-training		Post-training		1 month follow-up	
	Paretic	***Non-paretic***	***Paretic***	***Non-paretic***	***Paretic***	***Non-paretic***
% stance *	62 (1.7)	77 (1.4)	61 (1.9)	76 (1.4)	61 (2.0)	76 (1.0)
% double support *	19.7 (1.3)	20.5 (1.5)	19.4 (1.1)	17.2 (1.5)	19.5 (1.1)	17.3 (1.6)

* Values reported are the mean (standard deviation) across strides