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Practice structure and locomotor learning after stroke

Erin E. Helm, DPT, PhD², Ryan T. Pohlig, PhD³, Devina S. Kumar, MS², and Darcy S. Reisman, PT, PhD^{1,2}

¹Department of Physical Therapy, University of Delaware, Newark, Delaware

²Biomechanics and Movement Science Program, University of Delaware, Newark Delaware.

³Biostatistics Core Facility, University of Delaware, Newark, Delaware.

Abstract

Background and Purpose: The optimal characteristics of learning to promote recovery of walking have yet to be defined for the post-stroke population. We examined characteristics of task practice that limit or promote learning of a novel locomotor pattern.

Methods: Thirty-two persons with chronic hemiparesis were randomized to two conditions (CONSTANT and VARIABLE practice) and participated in two 15-minute sessions of split-belt treadmill walking. On Day 1, subjects in the CONSTANT condition walked on the split-belt treadmill at a constant 2:1 speed ratio, while subjects in the VARIABLE condition walked on the split-belt treadmill at three different speed ratios. On Day 2, both groups participated in 15 minutes of split-belt treadmill walking at the 2:1 speed ratio. Step length and limb phase symmetry metrics were measured to assess within-session learning (ie, Adaptation) on Day 1 and the ability to retain this new pattern of walking (ie, Retention) on Day 2.

Results: The amount of adaptation on Day 1 did not differ depending upon practice structure (CONSTANT and VARIABLE) for step length or limb phase (a)symmetry. The magnitude of reduction in asymmetry from Day 1 to Day 2 did not differ between groups for step and limb phase (a)symmetry.

Discussion/Conclusions: The results suggest that variable practice utilizing alternating belt speed ratios does not influence the ability of those with chronic stroke to adapt and retain a novel locomotor pattern. The effects of other forms of variable practice within other locomotor learning paradigms should be explored in those with chronic hemiparesis after stroke. **Video Abstract available** for more insights from the authors (see Video, Supplemental Digital Content 1. Video Abstract)

Keywords

motor learning; practice structure; locomotor learning; gait retraining; stroke

INTRODUCTION:

Recent evidence utilizing various locomotor adaptation paradigms indicates that those with chronic stroke and resultant hemiparesis retain the ability to adapt their walking to accommodate a novel locomotor pattern¹⁻⁴. Savin et al³ required subjects with hemiparesis as well as neurologically intact controls to overcome a novel swing phase resistance during treadmill walking. They found that both neurologically intact and chronic stroke subjects were able to adapt temporal and spatial parameters of gait. Those with chronic stroke however, differed in the rate of adaptation, requiring increased repetition during the late, slow phase of adaptation compared to controls. Tyrell et al⁴ also found that those with chronic stroke retain the ability to acquire a novel locomotor pattern when walking on a split-belt treadmill with the belts moving at two different speeds, however they adapted their walking pattern more slowly compared to neurologically intact individuals. In addition, stroke survivors also required more days of practice to acquire the novel locomotor pattern in comparison to neurologically intact controls. These results suggest that while those with chronic stroke may retain the ability to utilize trial and error practice to learn a novel motor skill, they appear to require additional practice or different practice parameters in order to optimize learning. Empirical evaluation of the parameters of motor learning which enhance locomotor learning and provide efficient and effective rehabilitation strategies for those post-stroke is currently lacking.

Motor learning studies of neurologically intact subjects demonstrate that variable practice paradigms improve motor learning relative to constant practice paradigms⁵⁻⁷. Within various upper extremity tasks in neurologically intact individuals, it has been demonstrated that task variability (variable practice) during initial performance results in improved retention while repetition of a task or blocked practice of several tasks (constant practice) during initial performance results in enhanced performance of the skill during the trial, however limits retention⁵⁻⁷. In a locomotor learning paradigm a form of variable practice compared to constant practice also resulted in improved retention in neurologically intact subjects⁸. Retention and generalization of motor skills are two benefits of variable practice that have led this paradigm to be promoted for use in neurorehabilitation.

Despite significant interest in practice structure within motor learning rehabilitation, few studies have examined variable practice to enhance motor learning after neurological insult^{9,10}. Furthermore, to our knowledge, a role for variable practice in complex motor learning tasks such as locomotion has yet to be addressed. Given that those with chronic stroke demonstrate increased errors and require increased practice^{4,11,12} disruption of steady state practice, which has been shown to be important for retention¹³, during variable practice paradigms may limit the ability to acquire a novel locomotor pattern.

In order to optimize rehabilitation post-stroke, it is important to understand whether a particular practice structure can improve post-stroke locomotor learning deficits. Therefore, the purpose of the current study was to examine the impact of task practice structure, specifically variable and constant practice, on locomotor learning in subjects with chronic stroke (>6 months post stroke). We hypothesized that chronic stroke survivors who participated in variable speed ratios of split-belt walking would demonstrate a decreased

magnitude of adaptation on the initial day of practice compared to subjects participating in a constant 2:1 speed ratio. However, with a subsequent day of testing, subjects participating in variable practice would demonstrate a faster rate of re-adaptation and increased retention of the novel locomotor pattern compared to subjects participating in constant practice.

MATERIALS AND METHODS

Participants

Subjects at least 6 months post-stroke were recruited from Delaware and surrounding states with the assistance of local physical therapists, physicians and advertising. All subjects provided written informed consent, with the study protocol approved by the University of Delaware Human Subjects Review Board. To be included, subjects must have sustained one single stroke, demonstrated the ability to ambulate independently with or without bracing, and walk for at least 4 minutes at a self-selected speed without assistance from another person. Exclusion criteria included history of cerebellar stroke, presence of cerebellar signs (ataxic gait or decreased coordination during rapid alternating hand or foot movements), neurologic conditions other than stroke, sensorimotor neglect, intermittent claudication, inability to walk outside the home prior to the stroke, or orthopedic problems of the lower extremities or spine that limited walking. In addition, those with a coronary artery bypass graft or myocardial infarction within 3 months, lower limb botulinum toxin injections within 4 months, or unexplained dizziness within 6 months of study participation were excluded.

Instrumentation and Procedures

All subjects participated in two consecutive days of split-belt walking. All subjects walked on a split-belt treadmill instrumented with two independent six degree of freedom force platforms (*Bertec Co.*, Columbus OH, USA) from which ground reaction force data was continuously collected at 1000Hz. Kinematic data was continuously collected using an 8-camera Vicon Motion Capture System (Vicon MX, Los Angeles, CA) at 100Hz. Retro-reflective markers (14-mm diameter) secured to rigid plastic shells were placed on the pelvis, bilateral thighs and bilateral shanks. Single markers were placed on the most prominent superior portion of the bilateral iliac crests, greater trochanters, medial and lateral knee joint lines, medial and lateral malleoli, bilateral heels, and the first and fifth metatarsal heads. During walking all subjects were instructed to gently rest fingertips on the treadmill handrail, and were given verbal cues, as necessary, to avoid excessive use of the handrail while walking.

All subjects wore a safety harness around their chest for fall prevention; however the harness did not provide body weight support. Heart rate and rating of perceived exertion (RPE) ¹⁴ were monitored throughout the treadmill walking sessions and subjects were provided with optional standing or sitting rest breaks. During optional rest breaks, subjects were not permitted to dismount from the treadmill. Blood pressure was monitored before and after walking and during rest breaks. All subjects were blinded to study hypothesis and group assignment.

Prior to split-belt treadmill walking on Day 1, subjects were asked to walk on the treadmill with the belts tied at a 1:1 ratio at their fastest speed possible for 1 minute, followed by a speed half of their fastest possible speed for 2 minutes in order to assess baseline step and limb phase asymmetry. To determine the subject's fastest possible speed, the treadmill speed was increased by 0.1 m/s until the subject reported inability to tolerate a further increase in speed or the researcher felt the subject would be unsafe at a faster speed. Following tied belt walking (BASELINE), subjects then participated in split-belt treadmill walking for 15 minutes. For each participant the split-belt configuration was set with the paretic leg placed on the slow belt. On the initial day of split belt walking, half of the subjects were randomly assigned to CONSTANT practice, while half were randomly assigned to VARIABLE practice.

Subjects in the CONSTANT condition were required to walk on the split-belt treadmill at a constant 2:1 speed ratio (Fig 1). The fast belt speed was set to the subject's fastest walking speed achieved during baseline testing as described above. The slow belt was set to half of the fast belt speed. This 2:1 speed ratio was maintained throughout the entire session on Day1.

Subjects in the VARIABLE condition were required to walk on the split-belt treadmill at three different speed ratios; 2:1, 1.5:1 and 2.5:1 (Fig 1). The 2:1 speed ratio was determined as described above for the CONSTANT group and is identified as the *base speed ratio*. The 2.5:1 speed ratio was calculated so that the fast belt speed was 80% of the fastest baseline speed collected for the base speed ratio. The 1.5:1 ratio was calculated based on 90% of the fastest speed collected for the base speed ratio. VARIABLE condition ratios were calculated as a percentage of the fastest speed possible to allow greater variations in speed ratios while avoiding the possibility of the participant experiencing a speed faster than they were capable of safely performing. The speed ratios were changed within the VARIABLE condition every 2.5 minutes so that the subject experienced each of the ratios twice (Fig 1). The subjects were not informed of the change in ratio and the treadmill continued to operate as the change in ratio occurred. All subjects started and concluded the 15 minutes of treadmill walking at their base speed ratio (2:1).

On the second day, both groups (CONSTANT and VARIABLE) participated in 15 minutes of split-belt treadmill walking at their individual base speed ratio (2:1) only. Subjects did not participate in tied belt walking on the second day or after split-belt walking on the first day (Fig 1).

Data Analysis

All kinematic and kinetic data were exported from Vicon-Nexus software, and further processed using Visual 3D (C-Motion, Inc, Germantown) and Matlab (MathWorks, Natick, MA). Gait events of foot strike and lift off were determined for each limb individually using an automatic algorithm in Visual 3D. Foot strike was identified when the vertical ground reaction force exceeded 20 Newtons for at least 8 frames, and lift-off identified when the vertical ground reaction force dropped below 20 Newtons for at least 8 frames. All gait events were visually checked for accuracy. Individuals participating in data processing of gait events were blinded to participant group assignment.

Dependent variables—Spatial and temporal parameters of gait have been found to respond differently during split-belt walking^{4,8,15}. Therefore, both spatial (step length) and temporal (limb phasing) variables were evaluated within the current study. Both variables were calculated for each leg continuously during treadmill walking. The spatiotemporal measure of step length was calculated as the sagittal distance between the right and left heel markers at foot strike. Step length was labeled as Left or Right based on leading leg. Stride by stride symmetry data for step length was calculated as:

(Step Length of Leg on Slow Belt - Symmetrical Step Length)

Symmetrical Step Length—Where symmetrical step length = (paretic step length + non-paretic step length)/2^{4,16}. Based on the above calculations, a value of 0 would indicate that the subject has achieved perfect symmetry based on their individual stride length. A negative value denotes the leg on the slow belt has a decreased step length relative to perfect symmetry. This method is preferred over the calculation of a ratio (paretic/non-paretic) because it prevents extremely large values when the denominator of the ratio is small due to a “step to” gait pattern in which one leg does not pass the other leg¹⁷.

Limb phase for each leg provides a measure of the difference in time between the contralateral limb’s peak flexion and the ipsilateral limb’s peak extension, normalized by the ipsilateral limb’s stride duration. This temporal measure was calculated as previously reported^{4,16}. Stride-by-stride limb phase symmetry was calculated by dividing the limb phase value for the leg on the slow belt by the contralateral limb phase value.

To evaluate differences in locomotor adaptation between the different practice conditions, we examined the *magnitude of total adaptation*, and *return to baseline*. To assess learning differences across days between the practice conditions we evaluated the magnitude of retention and the rate of re-adaptation on Day 2. Calculations were performed for both step and limb phase symmetry.

Magnitude of total adaptation. To evaluate the total amount of adaptation for both step length and limb phase (a)symmetry during split-belt treadmill walking, the magnitude of total adaptation was calculated as follows:

$$\text{Magnitude of Total Adaptation} = \text{Mean of Initial 10 Strides} - \text{Mean of Last 10 Strides}.$$

This calculation represents the difference between the (a)symmetry pattern utilized at the start of adaptation and the (a)symmetry pattern utilized at the end of adaptation. A larger positive number would indicate a larger amount of adaptation.

Return to baseline. To assess whether subjects were able to fully adapt back to their baseline (a)symmetry, the amount of adaptation relative to their individual baseline was calculated as follows:

$$\text{Return to Baseline} = \text{Mean of Last 10 strides} - \text{Mean of tied slow (Baseline)}$$

This calculation represents the difference between the (a)symmetry pattern achieved at the end of adaptation and the subject's baseline (a)symmetry pattern with the belts tied at a 1:1 speed ratio. A value of 0 would indicate the subject has completely adapted to the split-belt treadmill and has returned back to their baseline (a)symmetry pattern, despite the continued split-belts.

Magnitude of retention. If subjects have learned something about how to walk on the split-belt treadmill on Day 1, with re-exposure to the split-belt paradigm, on Day 2, subjects should have less step length or limb phase asymmetry^{4,8}. In particular, we would expect to see less step length or limb phase asymmetry at the start of split belt walking on Day 1 versus Day 2⁴. To assess this reduction in “error” from Day 1 to Day 2 the magnitude of retention was calculated as follows:

$$\text{Magnitude of Retention} = \text{Mean of first 10 strides Day 1} - \text{Mean of first 10 strides Day 2}$$

This calculation represents the difference between the initial adaptation on Day 1 relative to the initial adaptation on Day 2. A positive number would indicate that the subject was less perturbed by the split-belt treadmill on Day2 in comparison to Day1 and therefore has learned something about the split-belt treadmill paradigm.

Rate of re-adaptation. For each variable the rate of adaptation on Day1 and rate of re-adaptation on Day 2 was calculated by first removing baseline (a)symmetry from each raw symmetry value to provide a value that reflects the deviation from the individual's baseline (a)symmetry pattern^{4,16,18}. A value of 0 reflects a symmetry pattern identical to baseline (a)symmetry. Subtraction of the baseline (a)symmetry pattern allows for comparison of data across subjects who may demonstrate different levels of baseline asymmetry. A value of 30 strides was selected to represent *Early* adaptation and *Early* re-adaptation to step length asymmetry. Previous literature indicates that adaptation to limb phase asymmetry occurs on a much shorter timescale than step length adaptation^{4,8,16}. In order to accurately capture rapid adjustments in limb phase asymmetry we utilized the first 10 strides to assess *Early* adaptation and *Early* re-adaptation for limb phase. A linear model was used to compare the slope regressing *Early* re-adaptation (Day 2) on asymmetry between groups. An *a priori* decision was made to examine group level data linearly, only if greater than 70% of subjects within each group fell within the 95% confidence interval for a linear fit. To do this, each individual's stride data for asymmetry in *Early* re-adaptation were assessed using a modified Box-Cox test in SPSS¹⁹ (Draper, 1998). An interaction effect of stride by group was then tested in a linear regression model.

Statistical Analysis—Normality of the data distributions were assessed with the Kolmogorov-Smirnov test for normality. All statistical analyses were completed with SPSS v22. In order to account for any differences in the amount of practice on Day 1 between groups (VARIABLE vs. CONSTANT), the total number of strides during split-belt walking were tested (Table 1) to determine if total steps should be added as a covariate in the analyses.

To test our hypothesis that subjects who participate in variable speed ratios of walking would demonstrate a reduced *Magnitude of Total Adaptation* and *Return to baseline* on Day1, group differences (VARIABLE vs. CONSTANT) were assessed. Differences in limb phase for each dependent value were found to be non-normally distributed. As such group differences in limb phase were assessed utilizing the Mann-Whitney U test. Differences in step length symmetry for each dependent measure were tested using independent samples t-tests.

To test our hypothesis that participation in variable practice on Day 1 would result in an increased *Magnitude of Retention* on Day 2, the initial adaptation (mean of first 10 strides) on Day 1 was compared to the initial adaptation on Day 2. A mixed design analysis of variance (ANOVA) was utilized to compare the mean differences across days for each group (VARIABLE vs. CONSTANT). Analyses were performed for both step length and limb phase (a)symmetry.

A power analysis for sample size estimation was performed using G-Power ²⁰, utilizing the effect size required to detect a meaningful difference in the Magnitude of Retention from Day1 to Day2 from previous literature⁴. With a power of .80 and alpha level of $p=.05$ a total sample size of 24 ($N= 12$ per group) would be required to detect a difference in the magnitude of retention between groups.

RESULTS

A total of thirty two subjects participated in the study with sixteen subjects in each of the VARIABLE (58.72 $\pm$ 11.28 yr) and CONSTANT (62.28 $\pm$ 9.7 yr) groups. Table 1 contains participant demographics and baseline clinical scores. Groups did not differ significantly on any baseline demographics, clinical scores or total steps taken during practice (all p 's $>.05$).

Adaptation

Figure 2 illustrates the pattern of changes in step length asymmetry with exposure to the split-belt treadmill for individual subjects participating in VARIABLE and CONSTANT practice. At "baseline", with both treadmill belts set to the same speed, the individual subjects in the CONSTANT and VARIABLE practice groups demonstrate an asymmetric walking pattern relative to perfect symmetry (perfect symmetry= 0). When the treadmill belt speeds are set to a 2:1 speed ratio with the paretic leg walking on the slow belt and non-paretic leg walking on the fast belt, subjects demonstrate an increase in step length asymmetry relative to their baseline. The individual subject participating in the constant practice structure shows a pattern of adaptation similar to what has been previously reported ²¹. With a period of trial and error practice ("Adaptation"), the CONSTANT subject demonstrates the ability to reduce step length asymmetry despite the belts still moving at a 2:1 speed ratio (Fig 2). The VARIABLE subject also demonstrates the ability to utilize trial and error practice to reduce step length asymmetry over the course of 15 minutes on the first day. However, the VARIABLE subject demonstrates additional exaggerations of step length asymmetry each time the speed ratio is changed. Despite these repeated exaggerations, the

subject in the VARIABLE group appears to have adapted back to their baseline walking pattern by the end of practice on Day 1.

This qualitative pattern is confirmed through analysis of the *Magnitude of Total Adaptation* and *Return to baseline* for walking on Day 1 for the group data. The *Magnitude of Total Adaptation* on Day 1 does not differ significantly depending upon the practice structure (CONSTANT and VARIABLE) for step length (Table 2; $p=0.883$) or limb phase (Table 2; $p=0.491$) (a)symmetry (Fig 3). Similarly, there is no difference between groups in the asymmetry at the end of adaptation relative to baseline (Return to Baseline) for step length or limb phase (a)symmetry Table 2; $p=0.718$ and Table 2; $p=0.196$ respectively).

Learning

On a second day of practice, those in both the CONSTANT and VARIABLE practice conditions participated in split belt walking at a 2:1 speed ratio. If subjects learned something about how to walk on the split-belt treadmill, one would expect subjects to demonstrate a faster rate of re-adaptation and/or decreased magnitude of initial asymmetry upon re-exposure to the split-belt paradigm^{4,8}. Figure 4A and Figure 4B demonstrate this result for individual subjects in the CONSTANT (A) and VARIABLE (B) groups. The group data supports these individual results. Subjects in both the CONSTANT and VARIABLE practice groups demonstrate a reduction in the initial step length and limb phase asymmetry upon re-exposure to the split-belt treadmill on Day 2 ($p=.000$ for both). The magnitude of this reduction in asymmetry from Day 1 to Day 2, defined as the *Magnitude of Retention*, did not differ between groups for step and limb phase (a)symmetry (Fig 5A; $p=0.117$, $\eta^2_p=0.08$ and Fig 5B; $p=0.435$, $\eta^2_p=0.021$ respectively).

The results of the linear regression assessing rate of step length adaptation (Day 1) and re-adaptation (Day 2) showed similar results for subject's participating in CONSTANT and VARIABLE practice conditions (Fig 6). In the model for Day 1, Group and Stride (group step (a)symmetry values for each of the first 30 strides) predicted the change in asymmetry across strides ($R^2=0.772$; $p=0.000$; Table 3). Addition of the interaction term (Group $\times$ Stride) did not significantly improve the model ($R^2=0.002$; $p=0.48$; Table 3). In the model for Day 2, Group and Stride predicted the change in asymmetry across strides ($R^2=0.729$; $p=0.000$; Table 3). Addition of the interaction term (Group $\times$ Stride) significantly improved the model ($R^2=0.025$; $p=0.021$; Table 3), but this addition explained very little additional variance.

The results of the linear regression assessing rate of limb phase adaptation and re-adaptation between Day 1 and Day 2 also show similar results for subject's participating in CONSTANT and VARIABLE practice conditions (Fig 7). In the model for Day 1, Group and Stride (group step (a)symmetry values for each of the first 30 strides) predicted the change in asymmetry across strides ($R^2=0.456$; $p=0.006$; Table 4). Addition of the interaction term (Group $\times$ Stride) did not significantly improve the model ($R^2=0.000$; $p=0.92$; Table 4). In the model for Day 2, Group and Stride predicted the change in asymmetry across strides ($R^2=0.758$; $p=0.000$; Table 4). Addition of the interaction term (Group $\times$ Stride) did not significantly improve the model ($R^2=0.011$; $p=0.40$; Table 4).

DISCUSSION

Within rehabilitation, variable practice is often utilized to promote motor relearning and functional improvements in individuals post stroke. The use of this practice type is largely based on evidence from motor learning studies in neurologically intact individuals. To our knowledge, the current study is the first to assess the effects of practice characteristics on learning of a complex lower-extremity task in subjects post-stroke. The results of this study demonstrate that chronic stroke survivors are able to utilize variable practice to adapt and learn a novel locomotor pattern. Within the current study paradigm, however, the specific type of variable practice utilized confers little benefit over constant practice in learning of this novel locomotor task. Subjects participating in both variable and constant practice demonstrate a reduced initial perturbation on Day 2, indicating both groups have learned and retained something about walking on the split-belt treadmill. In comparison to previous studies in neurologically intact subjects, the specific type of variable practice utilized in this study does not appear to limit within-session learning, with similar amounts of adaptation noted between subjects participating in variable and constant practice on Day 1.

While the variable practice group does appear to have a larger magnitude of retention for both step length and limb phase (Fig. 6) this difference was not significant and the effect size was small (0.08 and 0.021 respectively). Similarly, rate of adaptation on Day 1 and Day 2 was not different between the constant and variable practice group. That is, despite a significant increase in the variability explained with the addition of the interaction term in the regression for step length on Day 2, the change in the variability explained was extremely small and likely not meaningful. These results demonstrate that the specific type of variable locomotor practice utilized in this study did not significantly enhance learning in individuals post stroke. Previous studies in neurologically intact individuals have demonstrated a role for switching between patterns in lower extremity motor learning⁸. The discordance in results between that study and the current one may be due, in part, to the difference in practice paradigms utilized. Malone et al⁸ utilized switching between normal walking and the same perturbation versus exposure to multiple different perturbations as presented in the current study. Thus, while the specific type of variable practice utilized in this study did not confer benefit in learning a novel walking task in people post-stroke, other forms of variable practice may generate different results.

Previous studies assessing the effects of variable versus constant practice in those with chronic stroke show mixed results for upper extremity tasks^{9,10,22}. Unlike the previous studies, the present study examined learning of a complex lower extremity task in those with chronic stroke. Our results cannot therefore be directly compared with previous studies, but appear to provide additional evidence that variable practice may not confer the same advantages after stroke as it does in neurologically intact subjects. It is plausible that the specific deficits to motor and cognitive processes post-stroke may limit the benefits of variable practice in motor skill acquisition and learning. Previous evidence in neurologically intact individuals indicates that separate neural substrates may be engaged during acquisition and consolidation of a motor learning task depending on practice structure^{7,23}. Lin et al⁷ demonstrated that TMS disruption to M1 during the inter-trial interval diminished performance and learning during variable, but not constant practice, implicating encoding

within M1 as crucial for learning enhancements of variable practice. Likewise, cortical damage as a result of cerebral infarct may differentially impact motor learning. Within the current study, many subjects demonstrate lesions involving M1, thus potentially impacting the ability to benefit from variable practice. Schweighofer et al¹⁰ demonstrated that the potential to exploit the benefits of variable practice in those post-stroke was dependent upon the integrity of subjects visuospatial working memory. Future studies assessing the impact of various practice paradigms and types of motor learning stratified by lesion location may provide further insight into the impact of stroke on motor learning.

The split-belt treadmill paradigm has previously been used to explore various aspects of motor learning including adaptation and retention of a novel locomotor pattern, but also allows exploration of the capacity of the nervous system for error recognition and correction. Recent evidence suggests exaggeration of post stroke gait asymmetry using the split belt treadmill can lead to after-effects resulting in a more symmetric pattern of walking on the treadmill as well as over ground^{1,2}. In addition, individuals post stroke demonstrate increased transfer of the split-belt walking pattern to over-ground ambulation². This increased transfer of the locomotor pattern to overground walking has been suggested to be due to difficulty in changing their walking pattern to environmental demands or context switching². This difficulty may also be present in the ability to learn a new locomotor pattern when the pattern is switched every 2.5 minutes as in the current study protocol. It has also been shown in neurologically intact subjects that variable practice within the range of errors naturally experienced can enhance generalization of the walking pattern learned on the split-belt treadmill to overground walking²⁴. Whether variable practice of the nature tested here would also facilitate transfer warrants further investigation.

The current paradigm demonstrates absence of benefit of variable practice to locomotor learning within a single session. Previous studies have demonstrated that individuals post-stroke require additional practice to adapt to and retain a novel locomotor pattern⁴, however these short term improvements in step-length asymmetry can be capitalized upon with repetitive exposure to the split-belt paradigm resulting in longer term improvements in gait post-stroke^{25,26}. It is possible that the current results are limited secondary to the short time frame of exposure. It is also plausible that the benefits of variable practice may not be adequately captured with the use of error-augmentation²⁷. A recent study by Lewek et al²⁷ demonstrated the use of error-augmentation to be non-superior to minimization of errors and verbal cuing when examining transfer of step-length asymmetry improvements to overground walking in individuals with chronic stroke.

Limitations

The current protocol was selected to allow a range of participants with varied physical impairment levels to participate in the study, and thereby increase generalizability of results. However, it cannot be discounted that a different variable speed and/or ratio protocol may have conferred different or more beneficial results related to retention. It is also possible that the current protocol did not offer enough variability or enough switches between patterns to enhance retention of the task beyond what was observed in the constant group. Increasing the variability of the task, although limiting the ability of some post-stroke to participate,

may demonstrate improved retention. Similarly, greater practice time overall or with each variable pattern may have improved retention. Additionally, the measure chosen to assess learning may impact the ability of variable practice to demonstrate its beneficial effects. The current study assessed learning by the ability to adjust ones walking pattern to the split-belt paradigm. Previous work utilizing the split-belt treadmill has assessed learning through generalization to overground walking² and carryover of the learned split belt pattern to tied-belt walking²⁸. Given the recent findings by Lewek et al²⁷ it is plausible that variable practice may demonstrate beneficial effects through alternate types of learning other than the use of error augmentation. Future studies may investigate the role of variable practice in generalization and transfer of the motor learning task to other activities, including overground walking in those with chronic stroke.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.
Experimental Protocol

Fig. 2. Individual stride by stride data for step asymmetry during tied belt walking at a 1:1 speed ratio for an individual CONSTANT subject (gray) and individual VARIABLE subject (black). The start of split-belt walking on Day 1 is depicted by double hash marks along the horizontal axis. A value of 0 represents perfect symmetry.

Fig. 3. Magnitude of Total Adaptation for step length (A) and limb phase (B). Dots are individual subject data; bars indicate group means. (Error bars = standard error)

Fig. 4.

Adaptation to Step Length Asymmetry for individual subjects participating in Constant (A) and Variable (B) practice paradigms on both days. Individual stride by stride data for step asymmetry during tied belt walking at a 1:1 speed ratio (Baseline) and during split belt walking on Day 1 and Day2 (Adaptation). A value of 0 represents perfect symmetry.

Fig. 5. Magnitude of Retention for step length (A) and limb phase (B) Dots are individual subject data; bars indicate group means. (Error bars = standard error).

Fig. 6.

Rate of adaptation and re-adaptation for step symmetry. Group averaged stride by stride data for step asymmetry over the first 30 strides of adaptation on Day1 (gray) and re-adaptation on Day2 (black) for subjects participating in Constant (A) and Variable (B) practice. Each data point represents the average of the individual step length asymmetry value per group for each stride.

Fig. 7.

Rate of adaptation and re-adaptation for limb phase symmetry. Group averaged stride by stride data for limb phase asymmetry over the first 30 strides of adaptation on Day1 (gray) and re-adaptation on Day2 (black) for subjects participating in Constant (A) and Variable (B) practice. Each data point represents the average of the individual step length asymmetry value per group for each stride.

Table 1

Subject Characteristics

	CONSTANT <i>(n=16)</i>	VARIABLE <i>(n=16)</i>
Age (years) (Std. Dev.)	62.28 ($\pm$ 9.7)	58.72 ($\pm$ 11.28)
Sex : Male (M)/Female(FM)	M: 7 FM: 9	M: 12 FM: 4
Type of Stroke * (Cortical/Subcortical/Mixed)	Cortical:3 Subcortical:5 Mixed: 7	Cortical:3 Subcortical:7 Mixed: 5
Time since Stroke (months) (Std. Dev.)	46.37 ($\pm$ 42.09)	34.06 ($\pm$ 29.01)
Lower Extremity Fugl Meyer (Std. Dev.)	21.12($\pm$ 5.30)	19.86 ($\pm$ 5.15)
Fast speed on treadmill (m/s) (Std.Dev.)	0.7 ($\pm$ 0.25)	0.81 ($\pm$ 0.28)
Total strides day 1 (Std. Dev.)	555.43 ($\pm$ 108.20)	587.50 ($\pm$ 133.44)

* N of 30, Information unavailable for 1 subject from each group.

Table 2

Non significant step and limb phase symmetry variables. Average and standard deviation for *Total Adaptation* (average of first 10 symmetry values - last 10 symmetry values) and *Return to Baseline* (average of last 10 symmetry values - baseline symmetry values).

Step Symmetry (m)		
	Total Adaptation	Return to Baseline
Constant	0.17 ± 0.07	0.02 ± 0.10
Variable	0.18 ± 0.10	0.00 ± 0.12

Limb Phase Symmetry		
	Total Adaptation	Return to Baseline
Constant	0.27 ± 0.18	0.22 ± 0.23
Variable	0.28 ± 0.26	0.33 ± 0.28

Table 3.

Sequential linear regression model predicting change in step length (a)symmetry over the first 30 strides for *Early* adaptation on Day 1 and *Early* re-adaptation on Day 2.

Rate of <i>Early</i> Adaptation: Day 1			
Model #	Predictors	R^2	R^2p
1	Group Stride	.772	.000
2	Group Stride Group $\times$ Stride	.002	.48

Rate of <i>Early</i> Adaptation: Day 2			
Model #	Predictors	R^2	R^2p
1	Group Stride	.729	.000
2	Group Stride Group $\times$ Stride	.025	.021

Table 4.

Sequential linear regression model predicting change in limb phase (a)symmetry over the first 30 strides for *Early* adaptation on Day 1 and *Early* re-adaptation on Day 2.

Rate of <i>Early</i> Adaptation: Day 1			
Model #	Predictors	R^2	R^2p
1	Group Stride	.456	.006
2	Group Stride Group $\times$ Stride	.000	.92

Rate of <i>Early</i> Adaptation: Day 2			
Model #	Predictors	R^2	R^2p
1	Group Stride	.758	.000
2	Group Stride Group $\times$ Stride	.011	.40