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## The Role of Movement Errors in Modifying Spatiotemporal Gait Asymmetry Post-Stroke: A Randomized Controlled Trial

**Michael D Lewek, PT, PhD,**

Division of Physical Therapy, Department of Allied Health Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599; Phone: 919-966-9732

**Carty H Braun, PT, DPT,**

UNC Health Care System, Chapel Hill, NC 27599

**Clint Wutzke, PhD, and**

Human Movement Science Program, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599

**Carol Giuliani, PT, PhD, FAPTA**

Division of Physical Therapy, Department of Allied Health Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599

### Abstract

**Objective**—Current rehabilitation to improve gait symmetry following stroke is based on one of two competing motor learning strategies: minimizing or augmenting symmetry errors. We sought to determine which of those motor learning strategies best improves overground spatiotemporal gait symmetry.

**Design**—randomized controlled trial

**Setting**—Rehabilitation research lab

**Subjects**—47 participants (59±12 years old) with chronic hemiparesis post-stroke and spatiotemporal gait asymmetry were randomized to error augmentation, error minimization, or conventional treadmill training (control) groups.

**Interventions**—To augment or minimize asymmetry on a step-by-step basis, we developed a responsive, ‘closed loop’ control system, using a split-belt instrumented treadmill that continuously adjusted the difference in belt speeds to be proportional to the patient's current asymmetry.

**Main Measures**—Overground spatiotemporal asymmetries and gait speeds were collected prior to and following 18 training sessions.

**Results**—Step length asymmetry reduced after training, but stance time did not. There was no group × time interaction. Gait speed improved after training, but was not affected by type of

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Corresponding Author: Michael Lewek, PT, PhD, University of North Carolina at Chapel Hill, 3043 Bondurant Hall, CB#7135, Chapel Hill, NC 27599-7135, Phone:(919) 966-9732, mlewek@med.unc.edu.

\*Dr. Braun is currently at Children's Hospital of Atlanta, Atlanta, GA 30303. Dr. Wutzke is currently at Department of Rehabilitation Science, George Mason University, Fairfax, VA 22030

asymmetry, or group. Of those who trained to modify step length asymmetry, there was a moderately strong linear relationship between the change in step length asymmetry and the change in gait speed.

**Conclusions**—Augmenting errors was not superior to minimizing errors or providing only verbal feedback during conventional treadmill walking. Therefore, the use of verbal feedback to target spatiotemporal asymmetry, which was common to all participants, appears to be sufficient to reduce step length asymmetry. Alterations in stance time asymmetry were not elicited in any group.

### Keywords

gait; stroke; asymmetry; adaptation; learning

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### Introduction

The slow walking speeds commonly observed following stroke are associated with marked temporal and spatial interlimb asymmetries in 48% and 44% of subjects, respectively.<sup>1</sup> Asymmetric gait has been associated with gait energetics,<sup>2</sup> gait speed,<sup>1</sup> and balance control,<sup>3</sup> and may lead to an increased risk of falls, lower extremity musculoskeletal injury,<sup>4</sup> and loss of bone mineral density in the paretic limb.<sup>5</sup> Because asymmetries are considered movement errors, therapists often use tactile, visual, or verbal cues to *minimize asymmetries* during gait training (error minimization strategy).<sup>6</sup> Indeed, conventional locomotor training on a treadmill has demonstrated improved gait speed,<sup>7-9</sup> but no effect on interlimb symmetry.<sup>7, 10, 11</sup>

In contrast, the approach of *augmenting asymmetry* (error augmentation strategy) to modify gait<sup>12-14</sup> is based on established motor learning principles, including error-based learning<sup>15</sup> and variability of practice.<sup>16</sup> Such an error augmentation strategy may be beneficial for individuals post-stroke due to their deficits in recognizing spatiotemporal asymmetries as movement errors.<sup>17</sup> The improved detection of augmented errors by muscle and joint proprioceptors may be the driving signal for adaptation and learning.<sup>15</sup> Walking on a split-belt treadmill with belts operating at different fixed speeds (e.g., 2:1 ratio with short step length limb on fast belt) is a prime example of augmenting error, which will initially exaggerate step length asymmetry.<sup>18</sup> The adaptation over time and resulting aftereffect suggest that the neuromuscular system retains the ability to produce nearly symmetric step lengths following stroke.<sup>18</sup> Long term training (e.g., 4 weeks) with this locomotor adaptation approach elicited significant improvement in step length symmetry in more than half of the trained individuals.<sup>19</sup>

Rather than using a fixed perturbation, motor learning may be accelerated by transient amplification of movement errors.<sup>20, 21</sup> To test this hypothesis, we designed a closed-loop feedback system coupled with an instrumented split-belt treadmill, in which step-by-step performance of spatiotemporal asymmetry determines the ratio of the belt speeds (i.e., error magnitude).<sup>22</sup> The system can either augment or minimize error on a step by step basis, by continuously adjusting the difference in belt speed to be proportional to the patient's current asymmetry. For example, if stance time is shorter on the paretic limb, the velocity of the

paretic treadmill belt can either be increased (to augment asymmetry) or decreased (to minimize asymmetry) relative to the non-paretic treadmill belt. With our unique system, we can determine which motor learning strategy (error minimization or augmentation) is best for improving overground spatial and temporal symmetry post-stroke.

Given that rehabilitation to improve gait symmetry may be based on one of these two competing motor learning strategies (i.e., minimizing or augmenting symmetry errors), the purpose of this randomized controlled trial was to determine which of those motor learning strategies best improves overground spatial and temporal gait symmetry in individuals with chronic hemiparesis post-stroke. Based on data from split belt adaptation work,<sup>18</sup> we hypothesized that training with error augmentation would elicit the largest change in overground gait symmetry, because this mode would enhance awareness of movement errors.

## Methods

### Setting and Participants

The study was a randomized controlled trial with three parallel groups. The trial was registered with clinicaltrials.gov (NCT01598675) and all subjects received medical clearance from a physician to participate in training and signed an informed consent form approved by the UNC-Chapel Hill IRB (study #11-1240). We recruited potential subjects with hemiparesis of >6 months duration after unilateral, supratentorial, ischemic or hemorrhagic stroke. Participants were recruited from local stroke support groups, email listservs, and referred by local physicians and physical therapists.

Potential subjects were included if they were able to walk >10 m overground without physical assistance, had an overground comfortable gait speed < 1.0 m/s (using assistive devices and bracing below the knee, as needed), were able to walk on a treadmill at >80% of comfortable gait speed using upper extremity support if needed, and exhibited stance time asymmetry and/or step length asymmetry. Asymmetry was defined by a Symmetry Ratio<sup>2</sup> ( $\max[\text{paretic}, \text{non-paretic}] / (\text{paretic} + \text{non-paretic})$ ) 0.524 for stance time asymmetry and 0.537 for step length asymmetry. These values represent a doubling of the upper 95% confidence limit of unimpaired individuals.<sup>1</sup> Potential subjects were excluded if they had uncontrolled cardiorespiratory/metabolic disease, other neurologic disorders or orthopedic injury that may affect gait, botulinum toxin to the lower limb in the past 6 months, or concurrent physical therapy.

### Randomization and Intervention

Following confirmation of eligibility and a double baseline ( $28 \pm 16$  days between baseline sessions), participants were randomized into one of three groups (Augmentation, Minimization, Control) by drawing a card from one of four envelopes that were stratified based on initial overground gait speed (< 0.5 m/s or >0.5 m/s, to help ensure similar gait speeds amongst groups)<sup>23</sup> and the type of asymmetry (step length or stance time). To avoid excluding subjects who had both stance time asymmetry and step length asymmetry, subjects were assigned, and trained accordingly, based on the larger of these two Symmetry

Ratios. Assessors assigned to perform all outcome measures were initially blinded to group allocation, however, due to staffing constraints the final four subjects were assessed by an unblinded assessor. All participants refrained from attending their usual physical therapy, if applicable, during the course of the study.

Subjects completed 18 sessions of walking for up to 20 minutes on a split-belt, instrumented treadmill (Bertec Corp, Worthington, OH) wearing a safety harness that did not restrict lower extremity movements. Subjects were permitted to hold onto the handrail, but were discouraged from doing so, if possible. Therapists did not facilitate limb movements. Verbal instructions, using external focus of attention to cue for increased symmetry (e.g., “ride the belt a little longer on your weak side”, “reach for a spot near the front of the treadmill”) were used for all groups, as necessary.<sup>6</sup> Heart rate and oxygen saturation were monitored throughout training and blood pressure was measured prior to, at mid-training (~10 minutes) and following each training session to ensure that blood pressure remained below 180/110 mm Hg.<sup>24</sup> Participants took rest breaks, as needed.

All three groups began each training session with two minutes of Control walking on the treadmill with both belts moving at the same speed, as a warm up. Then, without stopping the treadmill, subjects transitioned to the training phase (Asymmetry Augmentation, Minimization, or Control) for up to 18 minutes of additional walking. Each training session on the treadmill was followed by 10-15 minutes of overground gait training to encourage carryover of training to overground surfaces.<sup>6</sup> During overground training, subjects were permitted to use an assistive device, but typically practiced without, when possible. Similar verbal cues were used during overground and treadmill training.

### Treadmill Control

The treadmill was controlled by a novel computer-driven control algorithm. Treadmill control began by the therapist setting a base walking speed,  $v_{\text{base}}$ , which is the average speed of the two treadmill belts. During the first session, participants began walking at  $v_{\text{base}} = 80\%$  of comfortable gait speed for overground gait. The difference in speeds between the two belts,  $v_{\text{diff}}$ , was determined by the degree of the patient's asymmetry on a step-by-step basis:

$$\begin{aligned} \text{for Stance Time} \quad v_{\text{diff}} &= k * \log_2(\text{stance\_time}_{\text{right}} / \text{stance\_time}_{\text{left}}) * v_{\text{base}} \\ \text{for Step Length} \quad v_{\text{diff}} &= -k * \log_2(\text{step\_length}_{\text{right}} / \text{step\_length}_{\text{left}}) * v_{\text{base}} \end{aligned}$$

where  $k$  is a scale factor (default = 3), which can be increased to progress training so that a small amount of asymmetry will yield a larger difference in belt speed. Stance time or step length was calculated on a step-by-step basis from ground reaction force data (treadmill force plates) at 1080 Hz with a Vicon MX40+ system (Vicon/Peak, Los Angeles, CA). Stance time was the time (msec) that the vertical ground reaction force exceeded 10N, and step length was determined from center of pressure data as the anterior/ posterior distance between the feet at successive heel strikes<sup>25, 26</sup>. These data were sent to the application computer using VRPN.<sup>27</sup> The belt speed difference,  $v_{\text{diff}}$ , was applied to the treadmill by speeding up one belt and slowing the other:

$$\begin{aligned}v_{\text{right}} &= v_{\text{base}} - v_{\text{diff}}/2 \\v_{\text{left}} &= v_{\text{base}} + v_{\text{diff}}/2\end{aligned}$$

Augmenting asymmetry was achieved with a positive “k” value, whereas a negative “k” value was used to minimize asymmetry. Each belt had high and low speed limits applied for safety, such that the belt speeds would not exceed a 2:1 ratio.<sup>18</sup> Training step length or stance time was progressed similarly within and between sessions by altering treadmill speed and the “k” value. The “k” value was adjusted independent of treadmill speed (i.e.,  $v_{\text{base}}$ ). Treadmill speed was increased if heart rate remained below 70% of age-predicted maximum<sup>28</sup> or the perceived exertion was less than 14 on the Borg scale (for participants receiving medications that blunt heart rate response).<sup>24</sup>

### Outcomes and Follow-up

We collected overground gait characteristics from both baseline visits. Because of the tendency for gait speed to increase with repeated testing,<sup>29</sup> we used the overground data from the second baseline visit, which occurred one week prior to (Pre) training, and the repeated assessments at one week following the final training session (Post), and at one month after training (Follow-up). At each assessment visit, subjects were instructed to “walk at their normal, comfortable walking speed” as they performed 3 passes across a 14 foot GAITRite mat (CIR Systems, Franklin, NJ) with a 4 foot acceleration and deceleration zone at either end of the mat. GAITRite software was used to determine comfortable gait speed and gait asymmetry, as described above, for both step length and stance time variables.<sup>29</sup> Given the automated process of calculating outcome measures, we believe that the lack of blinded assessment for the final four subjects was inconsequential.

### Statistical Analysis

All data were exported into electronic spreadsheets (Excel 2016, Microsoft Corp) and data analysis was subsequently performed using SPSS (ver 23, IBM). Data residuals were checked for assumptions of normality using the Shapiro-Wilk test, and Mauchly's W was used to test for sphericity with the Huynh-Feldt adjustment, as needed. Primary (gait symmetry ratio) and secondary (comfortable gait speed) variables were analyzed using a two-way, repeated measures ANOVA (repeated for time) to assess the interaction effect (i.e., effect of time on the three groups: Augmentation, Minimization, Control). Tukey (between subjects) and Bonferroni corrected paired-samples t-tests (within subjects) were used for post-hoc tests. For those with step length asymmetry, the shorter step length can occur on either the paretic or non-paretic limb.<sup>18, 29</sup> We therefore sorted limbs based on which step was longer and shorter for separate comparison across time using a repeated-measures ANOVA. The relationship between changes in spatiotemporal symmetry and change in gait speed from Pre to Post training was assessed using Pearson correlations. Prior to enrollment, we performed a power analysis based on a non-central F-distribution to satisfy concerns about a potentially asymmetric distribution of our primary outcome measure (spatiotemporal asymmetry). Power was calculated using assumptions based on our review of reported changes in spatiotemporal asymmetry with locomotor training.<sup>10, 13, 30</sup> Estimating a standard deviation of 0.019 and a difference in the change in asymmetry of 0.035 from pre-

training to post-training, we expected to have greater than 80% power with sample size of 45.

## Results

We recruited 48 subjects to participate (26 in the step length symmetry training and 22 in the stance time symmetry training). As seen in the CONSORT diagram (figure 1), 37 subjects completed gait training (over a mean (SD) of 48 (10) days) and testing. The 3 groups did not differ on key baseline characteristics (table 1). The 11 subjects who dropped out were split between groups (Augmentation: N=4; Minimization: N=4; Control: N=3). Reasons for drop-out varied (transportation issues = 6; exercise intolerance = 2; blood pressure/cardiovascular issues = 2; none given = 1).

Overall, we observed a significant interaction ( $p = 0.026$ ;  $\eta^2_p = 0.140$ ) between time and the selected asymmetry parameter (i.e., step length or stance time asymmetry) indicating that those who were trained to alter step length vs stance time asymmetries responded differently over time. For this reason, all further analyses were separated by the participant's training parameter. No other interaction effects were significant (all  $p > 0.453$ ).

### Step Length Asymmetry

Twenty six subjects were assigned to perform training to improve step length asymmetry. Of those subjects, 21 (81%) completed testing and training (N=7: Augmentation; N=8: Minimization; N=6: Control). We observed no significant interaction effect (group  $\times$  time:  $p = 0.472$ ;  $\eta^2_p = 0.086$ ; figure 2) among the subjects who trained to improve step length asymmetry. Likewise, we observed no significant effect for group ( $p = 0.183$ ;  $\eta^2_p = 0.172$ ). We did, however note a significant effect of time on step length asymmetry ( $p = 0.005$ ;  $\eta^2_p = 0.311$ ). Across all groups, step length asymmetry was significantly higher (i.e., worse) at pre-test compared to post-test ( $p = 0.014$ ) and at follow-up ( $p = 0.045$ ). No difference was observed between post-test and follow-up ( $p = 1.000$ ).

To confirm that subjects did not simply improve their symmetry ratio by reducing the longer step length, we compared the step lengths of both limbs (table 3). Importantly, we observed that subjects significantly increased both their shorter ( $p < 0.001$ ;  $\eta^2_p = 0.621$ ) and longer ( $p < 0.001$ ;  $\eta^2_p = 0.701$ ) step lengths as a result of training, and maintained those improvements at follow-up (figure 3). Nine subjects (of 21) exhibited changes in step length asymmetry from pre- to post-training that exceeded the minimal detectable change (MDC) of 0.035.<sup>29</sup> Of those, one trained with error augmentation, five were in the error minimization group, and three were in the control group ( $p = 0.185$ ). Within this group that trained to improve step length asymmetry, we observed no change in stance time asymmetry ( $p = 0.774$ ;  $\eta^2_p = 0.012$ , table 2).

### Stance Time Asymmetry

We assigned 22 subjects to train to improve stance time symmetry and 16 (73%) completed training (N=5: Augmentation; N=6: Minimization; N=5: Control). Of those who trained to improve stance time asymmetry, there was no significant effect of time ( $p = 0.302$ ;  $\eta^2_p = 0.088$ ) on stance time asymmetry. Likewise, we observed no significant interaction effect

(group  $\times$  time:  $p = 0.374$ ;  $\eta^2_p = 0.146$ ; figure 4). These subjects were trained to improve stance time asymmetry, and thus we observed no influence of training on step length asymmetry ( $p=0.134$ ;  $\eta^2_p = 0.143$ ).

### Gait Speed

Because there were no significant interaction effects (all  $p>0.342$ ), the post-hoc analysis for gait speed was collapsed across all subjects. Gait speed significantly increased over time ( $p<0.001$ ;  $\eta^2_p = 0.617$ ). Specifically, we observed that subjects walked significantly faster after training (mean (SD) gait speed was 0.53 (0.28) m/s) compared to pre-training speeds (0.41 (0.24) m/s;  $p<0.001$ ;  $d = 0.52$ ). Gait speed continued to improve from the post-test to the follow-up session (0.56 (0.29) m/s;  $p = 0.018$ ;  $d = 0.08$ ).

Of those who trained to improve their step length asymmetry, we observed a moderate relationship between the change in step length asymmetry from pre- to post-training and the change in gait speed from pre- to post-training ( $r = -0.45$ ;  $p = 0.040$ ; figure 5). There was no such relationship between the change in stance time asymmetry and gait speed for those who trained to improve stance time asymmetry ( $r = -0.153$ ;  $p = 0.571$ ).

We performed one additional comparison because we were particularly concerned about the potential for training with error minimization to increase (i.e., make worse) subject's asymmetry.<sup>18</sup> Indeed, during training, our paradigm has the potential to augment step length symmetry while minimizing stance time symmetry, or vice versa. For example, a participant assigned to augment step length asymmetry during training may also have concomitantly minimized stance time asymmetry during training. For that reason, subjects were recoded as to whether step length asymmetry or stance time asymmetry was minimized or augmented (regardless of group assignment). In fact, we observed that the subjects ( $N=13$ ) who had their step length asymmetry errors minimized (either intentionally or not) showed a tendency to *reduce* their step length asymmetry from 0.592 (0.103) at pre-test to 0.556 (0.049) at post-test ( $p=0.097$ ;  $d = 0.48$ ). Those who had their stance time asymmetry errors minimized ( $N=13$ , regardless of intentional or unintentional) did not alter stance time asymmetry from pre-test (0.537 (0.014)) to post-test (0.539 (0.029));  $p = 0.682$ ;  $d = 0.12$ ). These data suggest that adaptive minimization of movement errors did not lead to an increase (worsening) in gait asymmetry following training.

### Discussion

Our hypothesis that gait training with error augmentation would improve spatiotemporal gait asymmetry more than minimizing errors was not supported by these data. Subjects were able to improve step length (spatial) asymmetry, but did not show an appreciable change in stance time (temporal) asymmetry following training. Despite this overall improvement in step length asymmetry after training, we did not observe one method of training to be superior to another. The common training component across all groups was the deliberate focus on spatiotemporal asymmetry and the verbal feedback from therapists during gait training. This attention to specific training variables through verbal feedback during functional practice may, therefore, have been the active ingredient that promoted improvements in step length asymmetry.



We are excited at the prospect that step length asymmetry was significantly improved, and that the improvement was retained for at least a month. Although the training was performed on a treadmill, all testing was performed overground, emphasizing the context-independent nature of the improvements. Although we were initially surprised that the error augmentation algorithm did not produce greater gains, from a clinical perspective this represents a more promising finding. Rather than requiring a split-belt instrumented treadmill with computer controlled algorithms, it appears possible to elicit substantial changes to step length symmetry in individuals with chronic stroke during “conventional” gait training; provided that appropriate focus, attention,<sup>31</sup> and variability in practice are provided.

Based on previous literature,<sup>19</sup> we were surprised that the error augmentation group did not outperform the other two groups. Although some have noted that error augmentation is more beneficial than error minimization during a single session,<sup>32</sup> others have reported that error augmentation did not improve the immediate retention of a locomotor balance task.<sup>33</sup> In our cohort, the type of error manipulation during training (either minimization or augmentation) did not appear to differentially influence spatial asymmetry changes; comparable changes occurred in all three groups. Importantly, however, we observed that step length symmetry was only improved in the subjects who trained to improve step length symmetry. We can think of two possible reasons for this. First, we couldn't train subjects to improve stance time asymmetry and expect to see an improvement in step length asymmetry. Despite the known relationship between spatial and temporal asymmetry,<sup>1</sup> the specific attention to step length asymmetry during training appeared important for eliciting change. Second, by the nature of the inclusion criteria, the subjects who trained to improve step length asymmetry exhibited greater step length asymmetry than those who trained to improve stance time asymmetry. Likewise, Reisman and colleagues demonstrated that responders appeared to have a larger baseline asymmetry than the non-responders.<sup>19</sup> Nevertheless, there were many individuals in our stance time asymmetry trained group (n= 9 of 16 who completed training) who exhibited substantial step length asymmetry, but happened to have stance time asymmetry that was larger in magnitude than their step length asymmetry. Therefore, although the difference in baseline step length asymmetry may have contributed to this finding, we think it is more likely that the change in step length asymmetry after training was due to the attention focused on that particular parameter.

We observed, similar to others,<sup>7, 10, 11, 13</sup> that stance time asymmetry is particularly resistant to change. As a rapidly adapting parameter,<sup>26</sup> stance time asymmetry is highly responsive to the speed of the treadmill belts, and thus did not change in response to training. Stance time is a reactive parameter, which relies heavily on peripheral feedback from hip flexor afferents, limb load receptors, and cutaneous feedback. The fact that after-effects are not observed after manipulation of stance time asymmetry suggests that this is a parameter that may not be modified using error manipulation.<sup>34</sup> Interestingly, even though stance time asymmetry and step length asymmetry are related to each other,<sup>1</sup> there was no concomitant change in stance time asymmetry in our group who trained to improve step length asymmetry. Thus, changing one parameter does not necessitate a change in another.<sup>35</sup>



Consistent with current neurorehabilitation strategies, which encourage spatiotemporal symmetry during training,<sup>6</sup> our “closed loop”, error minimization system was intended to produce nearly symmetric gait. There has been concern that such training may exacerbate gait asymmetry after training.<sup>18</sup> Instead, we observed that those who had their asymmetry errors minimized tended to reduce their asymmetry after 18 training sessions. Although this observation would appear to conflict with previous literature,<sup>18</sup> it is important to note the inherent difference in control schemes between our paradigm and that of others. Previous work has used open-loop systems, which are unresponsive to the step-by-step changes in movement that occur during training.<sup>18</sup> Instead, our “closed-loop” system puts the subject in the loop to ensure that the manipulation of errors is responsive to the subject's stepping. Our subjects in the error minimization and error augmentation groups, therefore, received real-time, proprioceptive feedback of gait asymmetry. Despite the likely presence of deficits in spatiotemporal asymmetry perception,<sup>17</sup> our subjects following stroke did not appear to need the altered proprioceptive feedback from the changing treadmill belt speeds, as subjects in all three groups were able to improve step length asymmetry.

The change in gait speed observed following training was comparable to previously published work.<sup>7, 36</sup> Although gait speed was increased within and across sessions, we focused our subject's attention on spatiotemporal gait symmetry rather than gait speed. Additionally, the gait speed change of our subjects was likely an underestimate compared to previous work. Because gait speed is known to increase substantially without the presence of an intervention,<sup>29, 37</sup> we performed a double baseline and used the second (i.e., faster) session's speed as the Pre-training speed. Notably, the change in step length asymmetry was related to the change in comfortable gait speed. Although this finding would seem to suggest that step length asymmetry is a therapeutic target for improving gait speed following stroke, there is evidence to the contrary. In short, we observed that several subjects experienced sizable increases in gait speed, with small changes in step length symmetry. Likewise, others have noted significant improvements in step length symmetry, without a concomitant change in gait speed.<sup>19</sup> Thus, we must question whether changing step length asymmetry is really necessary to elicit improvements in gait speed.

A limitation of this work is the large number of drop-outs. Getting participants to the lab for 18 training sessions proved more difficult than we anticipated given our budget limitations. Ultimately we had 77% (37 of 48) of our participants complete training, which was consistent with some recently reported gait training trials<sup>7</sup>, but a smaller percentage than others.<sup>38</sup> Despite the somewhat high drop-out rate, there were similar numbers of participants who did not complete training in each group. Additionally, the small sample size produced small cell counts within each stratification, which limited our ability to examine potential differences between individuals with a slow vs a fast walking speed. An additional limitation of this work is that the final four participants were not measured by a blinded assessor. Finally, additional information about specific lesion location might have helped with the interpretation of our data.

The differential response to training suggests that better selection criteria are needed to identify responders to treatment. We observed that nine of the 21 subjects trained to improve step length asymmetry exceeded the minimal detectable change.<sup>29</sup> Likewise, Reisman and

colleagues<sup>19</sup> demonstrated improvement in 7 of 13 subjects using a more liberal definition of “responder”. Although some individuals clearly had the capacity to improve their step length asymmetry, there are also some individuals who did not improve as a result of training. For those individuals who did demonstrate improvement in step length symmetry, only one reached the threshold for having symmetric gait. Presently, thresholds of minimally important clinical changes remain unknown for step length asymmetry. If further work to restore symmetric gait following stroke is to continue, it is important to determine the characteristics that makes someone successful at altering their step length asymmetry. Because the locomotor adaptation literature suggests that many individuals have the neuromotor capacity to produce improved symmetry,<sup>18</sup> perhaps verifying this capacity would improve subject selection for future work.

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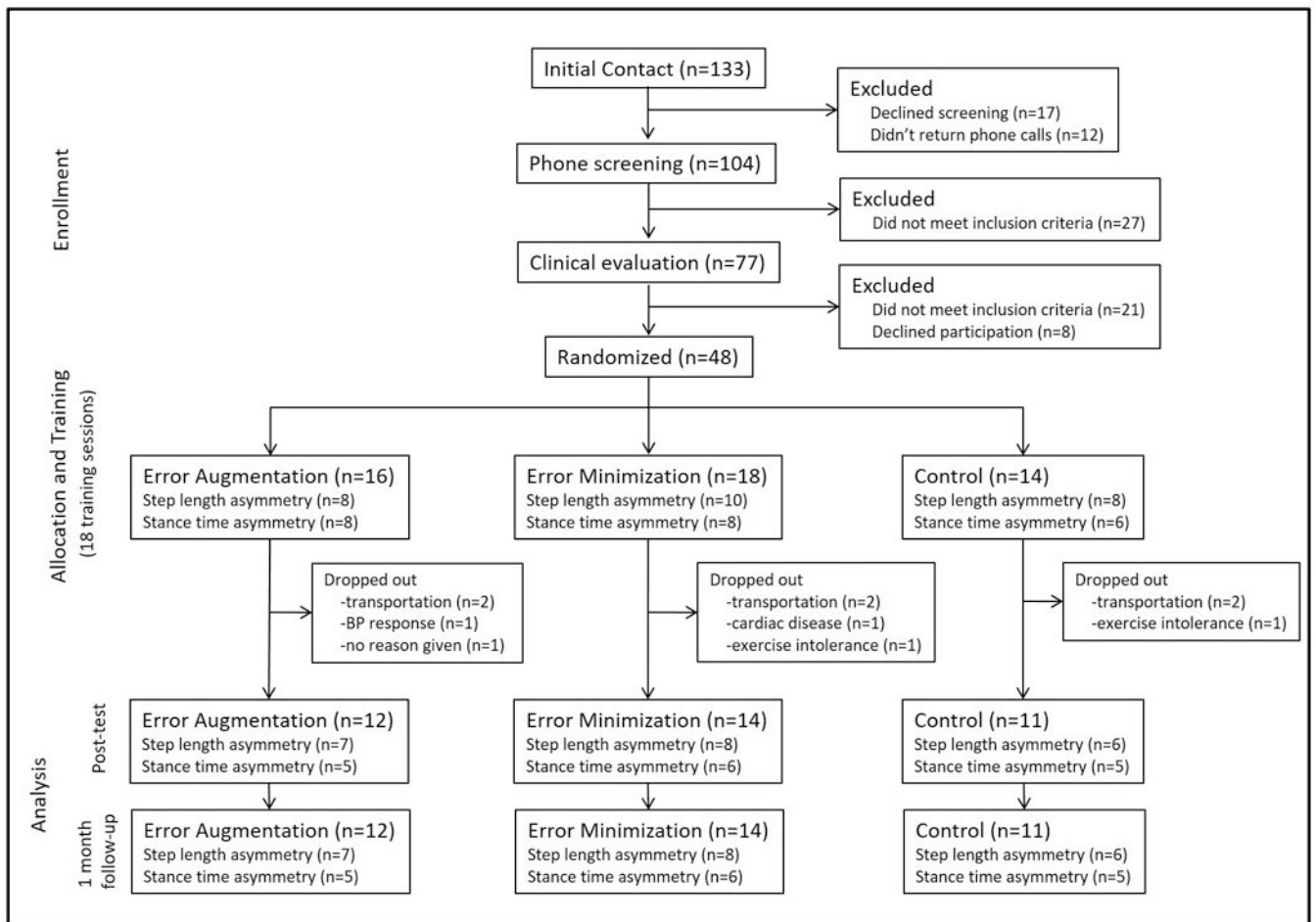
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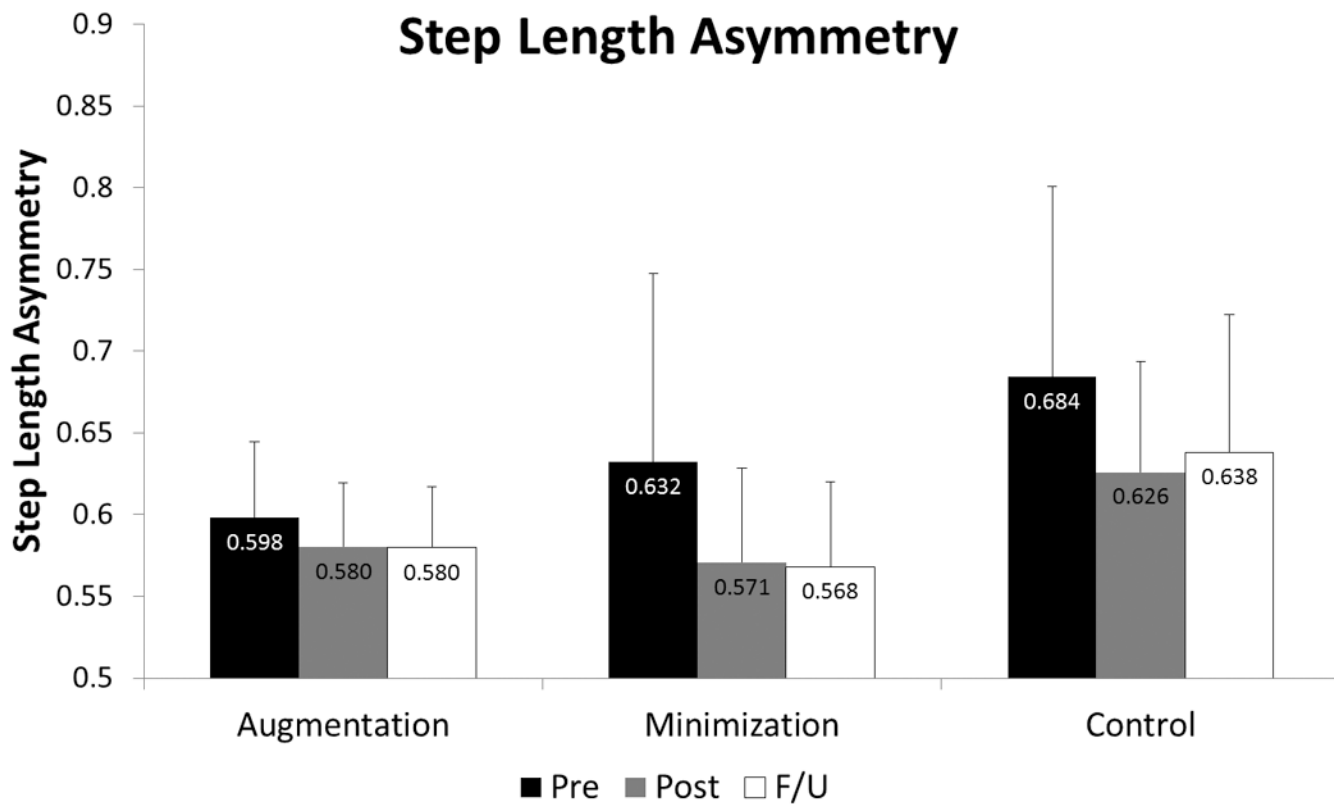
**Clinical Message**

- In patients more than six months after stroke and able to walk, persistent step length asymmetry was improved following training, whereas stance time asymmetry was not.
- A specific emphasis on either minimizing or augmenting asymmetry during treadmill training did not appear to influence these results.
- Verbal instruction and feedback were common across all groups and may have contributed to the noted improvement in step length asymmetry.

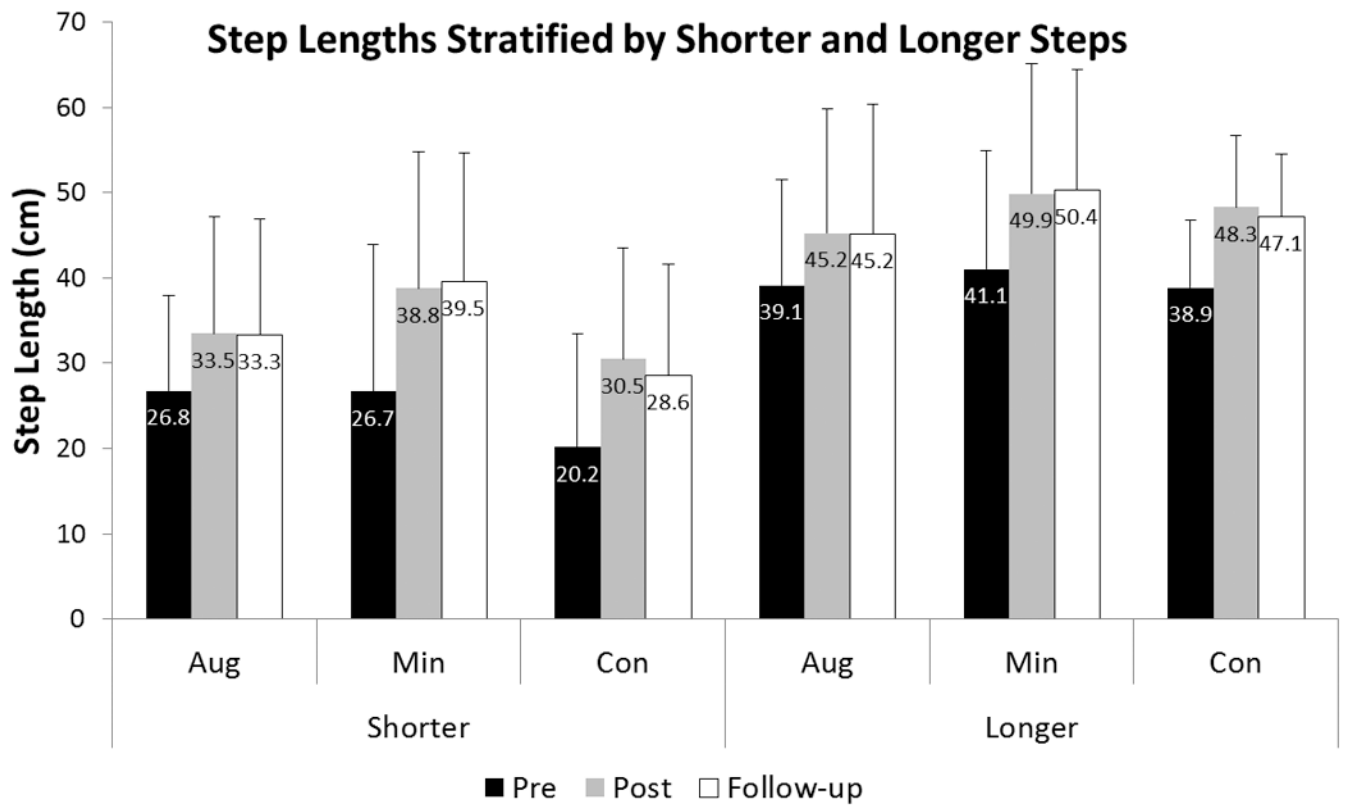


**Figure 1.** CONSORT diagram depicting subject allocation through study flow.



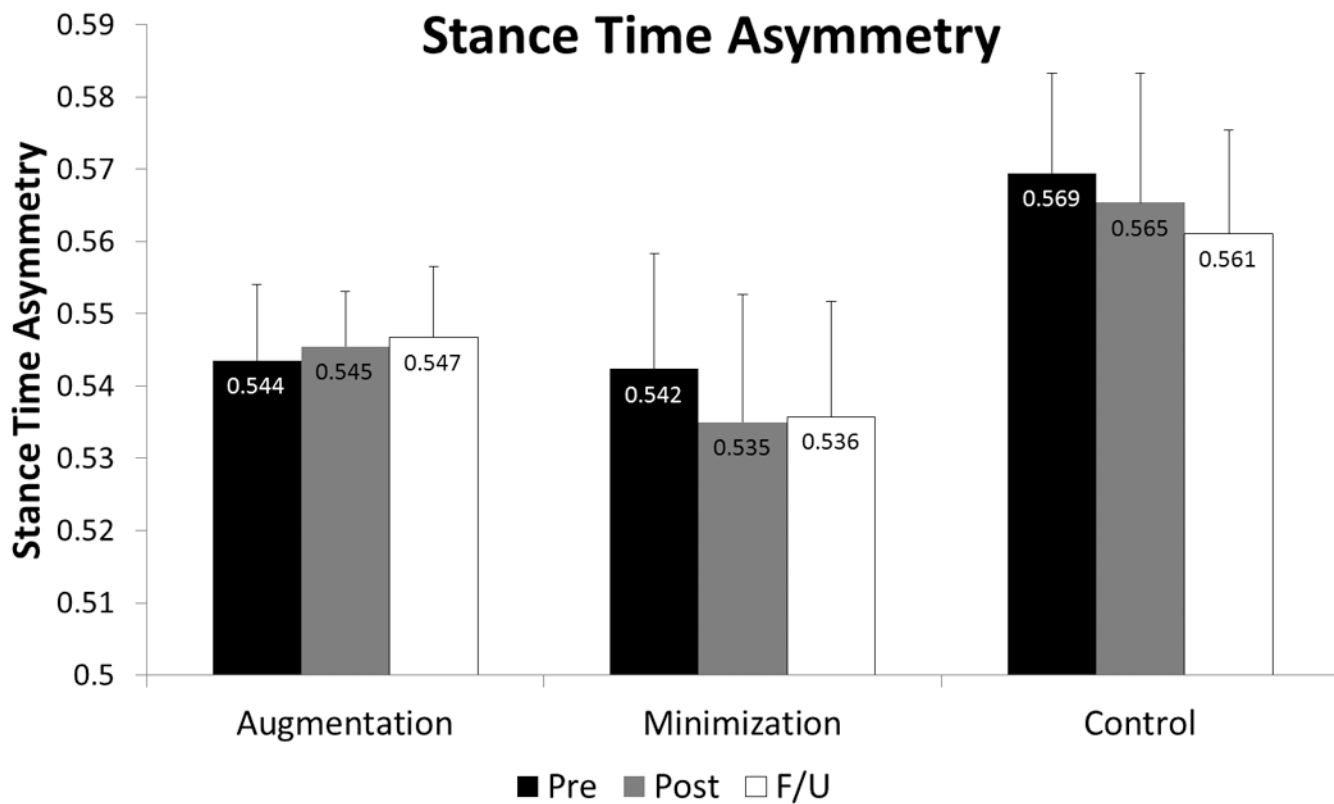


**Figure 2.** Step length asymmetry ratio (N=21) at the Pre-test (black), Post-test (gray), and Follow-up (white) time points for the Augmentation, Minimization, and Control groups. A significant effect of time was observed with step length asymmetry reducing from pre-test to post-test and persisting at follow-up.



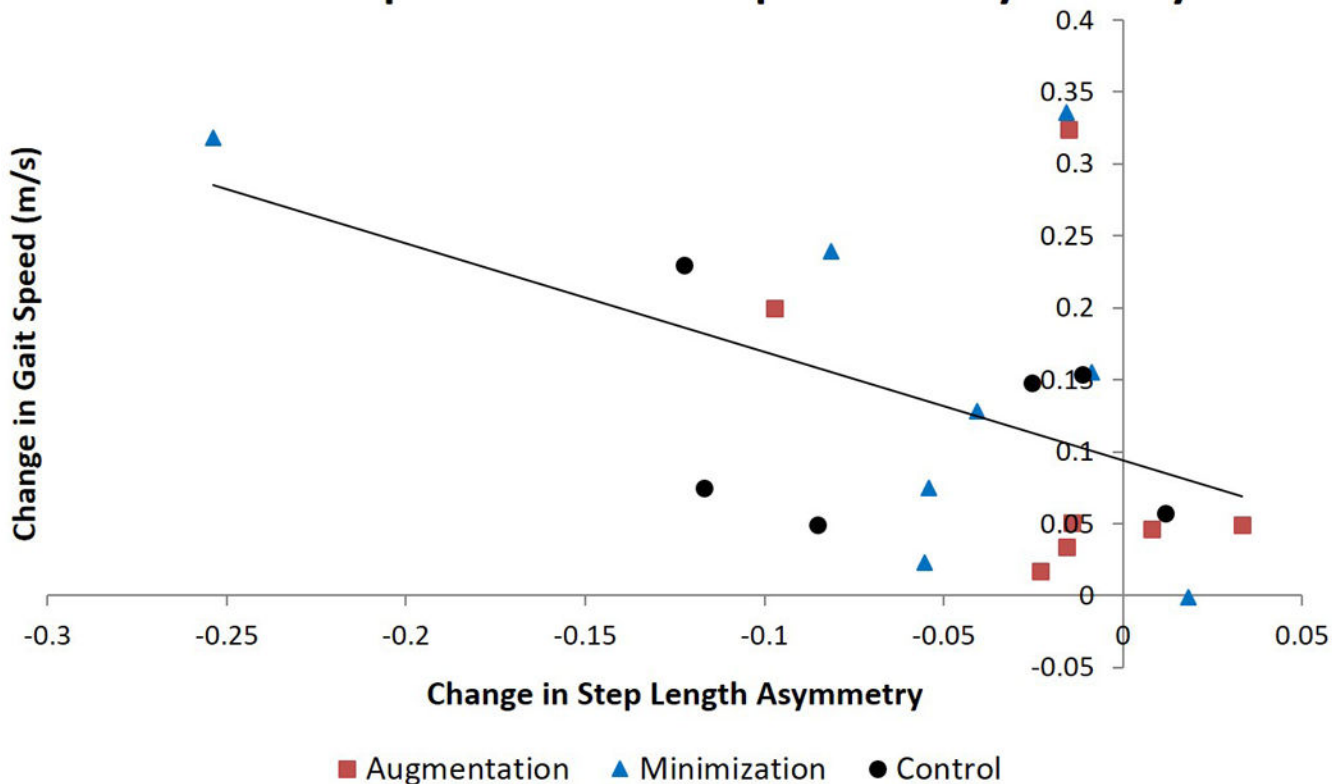
**Figure 3.**

Step lengths significantly increased from pre-test to post-test on both the limb taking the shorter step as well as the limb taking the longer step. These improvements persisted at follow-up on both legs.



**Figure 4.** Stance time asymmetry ratio (N=16) at the Pre-test (black), Post-test (gray), and Follow-up (white) time points for the Augmentation, Minimization, and Control groups. There was no effect of time, and no interaction effect to indicate that one group changed more than another.

## Relationship between Gait Speed and Symmetry



**Figure 5.** We observed the presence of a moderate relationship between the change in step length asymmetry and the change in gait speed from pre-training to post-training. Group allocation of individual subjects is shown.

**Table 1**  
**Subject Demographics**

	<b>Error Augmentation (n = 12)</b>	<b>Error Minimization (n=14)</b>	<b>Control (n=11)</b>	
<b>Age</b>	57.5 (10.5) years	60.7 (13.0) years	57.6 (13.2) years	p = 0.764
<b>Sex</b>	5 F / 7 M	5F / 9 M	5 F / 6 M	p = 0.916
<b>Paretic Side</b>	4 L / 8 R	9 L / 5 R	8 L / 3 R	p = 0.181
<b>Time Post-Stroke</b>	36.3 (21.7) months	54.4 (55.8) months	28.1 (27.9) months	p = 0.228
<b>Overground gait speed (Pre)</b>	0.42 (0.21) m/s	0.44 (0.28) m/s	0.36 (0.22) m/s	p = 0.710
<b>Assistive Device at pre-test</b>	6 canes, 6 none	10 canes, 4 none	9 canes, 2 none	p = 0.275
<b>Ankle bracing at pre-test</b>	3 yes, 9 no	7 yes, 7 no	9 yes, 2 no	p = 0.026

Values represent mean (SD).

Table 2

## Spatiotemporal Gait Asymmetry

			Pre-training	Post-training	Follow-up
Step Length Asymmetry Trained (N=21)	Augmentation		0.598 (0.046)	0.580 (0.039)	0.580 (0.037)
	Minimization		0.632 (0.115)	0.571 (0.058)	0.568 (0.052)
	Control		0.684 (0.116)	0.626 (0.068)	0.638 (0.084)
Stance Time Asymmetry	Augmentation		0.528 (0.013)	0.526 (0.013)	0.525 (0.016)
	Minimization		0.536 (0.022)	0.542 (0.028)	0.541 (0.028)
	Control		0.539 (0.020)	0.539 (0.017)	0.536 (0.019)
Stance Time Asymmetry Trained (N=16)	Augmentation		0.544 (0.011)	0.545 (0.008)	0.547 (0.010)
	Minimization		0.542 (0.016)	0.535 (0.018)	0.536 (0.016)
	Control		0.569 (0.014)	0.565 (0.018)	0.561 (0.014)
Step Length Asymmetry	Augmentation		0.527 (0.022)	0.531 (0.015)	0.517 (0.017)
	Minimization		0.521 (0.009)	0.517 (0.013)	0.520 (0.014)
	Control		0.533 (0.027)	0.539 (0.024)	0.533 (0.029)

Values represent mean (SD)



**Table 3**  
**Step Lengths (cm) Stratified by Shorter and Longer Steps**

		<b>Pre-training</b>	<b>Post-training</b>	<b>Follow-up</b>
Shorter Steps	Augmentation	26.8 (11.2)	33.5 (13.7)	33.3 (13.6)
	Minimization	26.7 (17.3)	38.8 (16.0)	39.5 (15.1)
	Control	20.2 (13.3)	30.5 (13.1)	28.6 (13.1)
Longer Steps	Augmentation	39.1 (12.4)	45.2 (14.6)	45.2 (15.3)
	Minimization	41.1 (13.9)	49.9 (15.3)	50.4 (14.1)
	Control	38.9 (7.9)	48.3 (8.5)	47.1 (7.4)

Values represent mean (SD)