# Study 2: Characterize adaptations to unilateral Phase-Dependent Speed Variation and conventional split-belt treadmill in healthy subjects.

## Introduction

More than 9 million adults in the United States have had a stroke, with approximately 900,000 new survivors of stroke each year, resulting in annual costs exceeding $50 billion (Tsao et al. 2023). Stroke is the largest cause of severe and complex disability, which often includes difficulty walking(Adamson, Beswick, and Ebrahim 2004). A hallmark of post-stroke gait is asymmetric step length, which is associated with asymmetrical force production and stroke severity(Balasubramanian et al. 2007). Split Belt Treadmill (SBT) training, which uses side-by-side belts moving at different speeds, induces spontaneous changes in step length and gait mechanics without explicit feedback(Reisman, Block, and Bastian 2005; Reisman et al. 2007). For individuals with post-stroke hemiparesis, repeated SBT training improves step-length symmetry and enhances walking speed (Reisman et al. 2013; Betschart, McFadyen, and Nadeau 2018). This project introduces an innovative SBT protocol variation that may evoke novel biomechanical adaptations, potentially improving upon the benefits of conventional SBT (cSBT) training.

### **cSBT Training Mechanism**

In cSBT training for post-stroke gait asymmetry, the shorter-step side is assigned to the faster belt(Reisman, Block, and Bastian 2005; Reisman et al. 2007). This initially exaggerates asymmetry but evokes feed-forward changes that gradually restore baseline asymmetry(Reisman, Block, and Bastian 2005; Reisman et al. 2007), provided individuals have intact cerebellar function(Morton and Bastian 2006). When belt speeds are subsequently equalized, a temporary overcorrection towards symmetry occurs (Post Adaptation), foreshadowing potential long-term improvements with repeated practice(Reisman et al. 2013; Betschart, McFadyen, and Nadeau 2018). As individuals with hemiparesis can present with longer paretic steps or longer non-paretic steps(Balasubramanian et al. 2007), the fast-belt assignment varies. The Step Length Ratio (SLR), defined as , thus guides cSBT training.

**Error Augmentation Strategy for Split-Belt Treadmills**

Longer Paretic Step (LPS) à Non-Paretic Side Fast

*Longer Non-Paretic Step (LNPS) à Paretic Side Fast*

### **cSBT Training Limitation**

cSBT training induces Post Adaptation reductions in ankle plantarflexor (PF) torque on the fast side and increases on the slow side, in both healthy and post-stroke subjects(Lauziare et al. 2014). These PF torque changes correlate with contralateral step length alterations, affecting the SLR. Given that hemiparetic gait typically features reduced paretic PF torque(Allen, Kautz, and Neptune 2011), and PF torque is crucial for forward propulsion(Neptune, Kautz, and Zajac 2001; Liu et al. 2006; Hsiao et al. 2015), this effect may have negative implications for individuals with a Longer Non-Paretic Steps (LNPS)(Lauziare et al. 2014). *Normalizing SLR via cSBT may inadvertently amplify paretic side joint deficits*. Here we propose a novel approach to alter SLR therapeutically without compromising PF torque.

**Split-Belt Treadmill Impact on PF Torque**

Non-Paretic Side Fast à Paretic PF Torque ↑

*Paretic Side Fastà Paretic PF Torque↓*

### **Phase-Dependent Speed Variation (PDSV)**

We postulate that the cSBT task can be decomposed into two distinct perturbations, each inducing unique adaptations:

**A comparison of the legs and the bones of the human body

Description automatically generated with medium confidence“FastBrake”** (stepping onto a faster belt): The leading limb generates braking force while pushed posteriorly at a faster speed toward the slower trailing limb. This change in relative foot position increases the subsequent slow-side step length. The adaptation decreases slow-side step length, correlating with decreased fast-side PF torque (Lauziare et al. 2014) (Figure 1a).

Figure 1: PF Torque Impacts Step Length Bilaterally

**“FastProp”** (stepping off a faster belt): The trailing limb generates propulsive force while pulled away from the slower leading limb. This changes the relative foot position, decreasing the subsequent fast-side step length. The adaptation increases fast-side step length. As this perturbation occurs in late stance when plantarflexors primarily contribute to ipsilateral swing(Neptune, Kautz, and Zajac 2001) (Figure 1b), we predict an increase in ipsilateral (fast-side) PF torque.

To isolate these perturbations, we propose Phase Dependent Speed Variation (PDSV), which alters belt speed in synchronization with the gait cycle. Using real-time vertical Ground Reaction Force (GRF) monitoring, the belt speed is modulated between fast and slow on the target side based on two GRF triggers: when the target limb enters swing (vertical GRF → 0) and when it begins to bear more vertical GRF than the contralateral limb.

Specifically, in FastBrake, the left belt accelerates to 2 m/s during left swing. At left initial contact, there is a disparity between belt speeds that forces the left foot toward the right foot. When the left foot bears 50% of the total vertical GRF, the belt begins to slow to 1 m/s. The 1 m/s speed is reached by the time the right foot makes initial contact so that the feet are not pushed together during right-leading double support.

In contrast, in FastProp, the left belt slows to 1 m/s during left swing. At left initial contact, the two belt speeds are equal. When the left limb begins bearing 50% of the total vertical GRF, the left belt begins to accelerate to 2 m/s as the right limb enters swing. When the right foot makes contact with the right belt traveling at 1 m/s, the left belt is traveling at 2 m/s and the left foot is dragged away from the right foot.

This approach produces belt speed profiles show in Figure 2.

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Figure 2: Belt speed across stance phase by condition as recorded by markers on belts. During double support the leading limb is in early stance and the trailing limb is in late stance. Disparities in belt speed between leading and trailing limbs during double support will cause the feet to be pushed together or pulled apart.

Isolating these perturbations may allow for selective application of the most clinically relevant intervention. For individuals with longer non-paretic steps, applying only FastProp to the paretic side could increase paretic step length without reducing paretic PF torque. Alternatively, for those with longer paretic steps, administering only FastBrake to the non-paretic side could increase non-paretic step length, improving asymmetry with a briefer, potentially less disruptive gait perturbation.

## **Methods**

### **Participants**

We will recruit 20 healthy adults (18-45 years) from central Texas. Inclusion criteria: ability to walk unassisted for 20 minutes. Exclusion criteria: pregnancy, lower extremity orthopedic, neurological, vascular, or metabolic conditions affecting gait.

### **Data Collection**

We will use a 10-camera Vicon Nexus motion capture system (100 Hz) and an instrumented split-belt treadmill with handrails (Motek Medical, 1000 Hz). Participants will wear a safety harness, and a 7-segment lower body marker set. Static and dynamic calibration trials will be performed, including functional calibration of hip and knee joints using "hula hoop" and "quarter squat" movements (Schwartz and Rozumalski 2005).

### **Protocol**

Participants will complete trials for three conditions in a randomized order (cSBT, FastBrake, FastProp) as outlined in Table 1. These will be randomized along with two additional conditions as outlined in Study 3.

Table 1: Randomly ordered trials in Study 2 (Study 3 Trials in faded font)

|  |  |  |
| --- | --- | --- |
| **Randomly Ordered Trials** | | |
| **Study** | **Condition** | **Description** |
| 2 | cSBT | Left belt at 1 m/s and right belt at 2 m/s |
| 2 | Unilateral FastBrake | Left belt runs 2 m/s at left foot contact, then slows to 1 m/s beginning after weight shift is 50% complete |
| 2 | Unilateral FastProp | Left belt runs 1 m/s at left foot contact, then increases to 2 m/s beginning after weight shift is 50% complete |
| 3 | Bilateral FastBrake | Belts run 2 m/s at foot contact, then slow to 1 m/s beginning after weight shift is 50% complete |
| 3 | Bilateral FastProp | Belts runs 1 m/s at foot contact, then increase to 2 m/s beginning after weight shift is 50% complete |

Each trial consists of 3 minutes baseline walking (1 m/s), 6 minutes perturbed walking, and 3 minutes post-adaptation (Figure 3). This protocol structure aligns with previous research demonstrating detectable changes in PF torque following Adaptation(Lauziare et al. 2014). We employ a 2:1 speed ratio. This can be largely adapted to within approximately 25 strides (Reisman, Block, and Bastian 2005). Given typical stride times are less than 1.5 seconds each(Wang et al. 2019) , our 6-minute adaptation period should allow ample time for full adaptation, with 3 minutes sufficient for subsequent washout.

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Figure 3: Structure of each trial and indicators of where measurements occur for each Period (Late Baseline, Early Adaptation, Late Adaptation, Early Post Adaptation)

Participants will wear a safety harness and receive verbal countdowns before speed changes. Ground reaction forces will be recorded, and D-Flow software (v3.20.0) will control belt speeds based on vertical GRF. Rating of Perceived Exertion (RPE) will be collected using a Borg RPE 10-point scale (Borg et al. 2010) during the final minute of Baseline and Adaptation. 60-second recordings will capture late baseline (30 s)/early adaptation (30 s) and late adaptation (30 s)/early post-adaptation (30 s) transitions. Handrails will be available if needed, though participants will be asked to avoid their use unless necessary to preserve balance.

### **Split Belt Control Mechanism**

For PDSV trials, custom D-Flow scripts will trigger left belt speed changes based on force plate data: at left swing initiation when GRF goes to zero and then when the left vertical GRF exceeds the right vertical GRF. The baseline speed is 1 m/s, and the fast speed is 2 m/s, with transitions limited by the M-Gait's maximum belt acceleration of 3 m/s2.

### **Rationale for Target Belt Speeds**

Healthy individuals walking at ≥1 m/s have a swing time of ~0.33 seconds (Wang et al. 2019), allowing a 1 m/s speed change between double support phases. This allows for a roughly even distribution of fast and baseline speeds across the braking and propulsive phases of stance (see Figure 2). The 2:1 speed ratio (1 m/s slow, 2 m/s fast) is well-tolerated in healthy individuals(Reisman, Block, and Bastian 2005) and elicits detectable after-effects in ankle joint torque(Lauziare et al. 2014).

### **Data Processing**

Visual3D (HAS Motion, Kingston, Ontario) software will perform data filtering and biomechanical calculations. Marker trajectories and GRF will be smoothed using second-order Butterworth low-pass filters at 6 Hz. Center of Pressure data will be smoothed using second-order Butterworth filters at 4 Hz. This lower frequency filter removes an oscillatory artifact in the treadmill’s COP data that is present during early stance across all trials, including baseline walking. With this filtering, progression of COP across the foot aligns with typical patterns of progression(Chiu, Wu, and Chang 2013). Joint centers will be defined by malleoli markers (ankle) and functional calibration methods (hip and knee)(Schwartz and Rozumalski 2005).

Joint torques will be normalized to body weight. Joint torque profiles across stance phase will be time-normalized and averaged across five steps to characterize torque in each Period (Figure 4). PF impulse will calculated by summing across the time-normalized joint torque profile when there is a net PF moment, and then multiplying by the mean stance time.

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Figure 4: Joint torques normalized to body weight across stance phase. These curves are the average of 5 stance phases. Negative values represent a net plantarflexor moment.

Actual belt velocity will be calculated using reflective markers affixed to the belts and custom Python scripts within Vicon. Onset and completion of the Adaptation period will be identified by this belt velocity. Primary Variables for Late Baseline and Early Post Adaptation will be characterized by averaging the last 5 complete steps of Baseline and first 5 complete steps of Post Adaptation, respectively. An average of 5 steps before and after alterations in belt speed successfully identified step length symmetry and PF torque changes from Baseline to Post Adaptation in previous research(Lauziare et al. 2014). Secondary variables for Early and Late Adaptation will be similarly calculated.

### Primary Variables

**Step Length Ratio** (SLR) defined as where step length is the distance between heel markers at initial contact of the leading limb

**Left (fast side) ankle PF impulse** during stance. PF Impulse will be normalized to body weight.

Primary variables will be examined for Late Baseline and Early Post Adaptation

### Secondary Variables

Dominant lower limb will be assessed by asking “If you were to kick a soccer ball into a goal, which foot would you kick with?”(van Melick et al. 2017). RPE will be assessed in the final minute of each baseline and adaptation period.

Lower extremity joint torques will be calculated for all four periods (Late Baseline, Early Adaptation, Late Adaptation, Early Post Adaptation).

### Hypotheses

(H1) *SLR*: Main effect for Period, with increases in SLR from Baseline to Post Adaptation across all conditions, indicating PDSV can alter SLR in a similar direction as cSBT.

A diagram of different types of changes

Description automatically generated with medium confidence(H2) *Fast Side PF Impulse*: Main and interaction effects for Condition and Period on left (fast) side PF impulse. Comparing Late Baseline and Early Adaptation, cSBT and FastBrake will decrease PF Impulse, while FastProp will increase it.

Figure 5: Hypothesized Effects on Primary Variables

A graphical depiction of the expected outcomes on primary variables is shown in Figure 5. Preliminary results for SLR can be found in Figure 6B (comparing Baseline to Post Adaptation) and preliminary results associated with Altered side PF impulse can be found in Figure 8.

These findings would suggest that FastProp may be able to improve SLR in individuals with a LNPS, while also increasing paretic PF impulse. Additionally, FastBrake may be able to evoke similar adaptations as a cSBT while perturbing a smaller portion of the gait cycle and potentially being easier to tolerate.

### Statistical Analysis

*Hypothesis Testing*

To assess the effects of the different split-belt treadmill protocols on primary variables, we will employ a linear mixed-effects model. Step Length Ratio (SLR) and Left (altered side) PF impulse will be analyzed across Periods (Baseline and Post-Adaptation) and Conditions (cSBT, FastBrake, and FastProp). The model will include fixed effects for Period and Condition as well as their interaction. A random intercept for Participant will be included to account for within-subject variability.

Pairwise comparisons of periods within each condition will be used to assess specific intervention, applying Holm's correction for multiple comparisons.

All analyses will be performed in R, using the lme4 package for mixed-effects modeling and the emmeans package for post-hoc comparisons. Statistical significance will be set at α = 0.05 for all tests.

*Assessing Potential Confounds*

To assess potential order effects and carryover effects, we will use a mixed-effects model with condition order and previous condition as fixed effects and participant as a random effect. This analysis will be performed on the primary outcome measures (SLR and PF impulse).

If significant order effects or carryover effects are detected, we will adjust our primary analysis strategy to include condition order and/or previous condition as a fixed effect.

*Alternative Outcomes*

If expected changes are not observed, we will examine differences in gait parameters during late adaptation to potentially explain variations in post-adaptation step symmetry and PF impulse. Potential compensatory mechanisms include (a) increased cadence to avoid peak FastProp times and (b) increased hip flexor torque to substitute for PF torque in facilitating limb swing.

Additionally, participant specific factors will be examined that may differentiate individuals who respond in an unexpected manner, pointing toward protocol improvements. For example, shorter-legged individuals may experience difficulty with the speed settings suggesting that a more individualized set of parameters should be used.

## Preliminary Results

Data has been collected and analyzed for 5 subjects.

### Step Length Ratio

Preliminary testing of PDSV largely aligns with the expected impact on SLR (Figure 6 and Table 2). Across all three conditions, the step-length ratio begins with symmetry. Immediately upon initiation of the perturbation, the ratio shifts below one, indicating that the fast (altered) side step length reduces. This asymmetry diminishes as the participant adapts across six minutes of sustained perturbation. Upon removal of the perturbation and return to matched belt speeds, there is an overcorrection in the opposite direction of the early adaptation asymmetry.

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Figure 6: A) The typical shifting of step length ratio in a conventional split belt task (symmetry, perturbation, correction, over-correction) B) Preliminary data replicates this for the conventional split belt condition; Phase Dependent Speed Variation produces similar patterns of adaptation.

Table : Step Length Ratio across conditions and periods.

|  |  |  |  |
| --- | --- | --- | --- |
| **Step Length Ratio Across Periods by Condition\*** | | | |
|  | **Conventional Split Belt Treadmill** | **Unilateral FastBrake** | **Unilateral FastProp** |
| Baseline | 1.00 (.02) | .99 (.06) | .97 (.05) |
| Early Adaptation | .66 (.07) | .78 (.15) | .76 (.24) |
| Late Adaptation | .94 (.12) | .88 (.06) | .94 (.08) |
| Early Post Adaptation | 1.49 (.47) | 1.32 (.28) | 1.26 (.21) |
| \* mean (sd) |  |  |  |

### PF Torque Profiles

In our initial subjects, we are largely able to replicate the joint torque profiles observed by Lauziare et al (2016) following the conventional split belt task (Figure 7). The FastBrake condition appears to parallel the cSBT in the suppression of altered side plantarflexor torque. The FastProp condition appears to exhibit in increase in PF torque, particularly during mid stance.

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Figure 7: A) Ankle joint torque profiles across all subjects as observed by Lauziare et al (2014). Dotted lines are from late baseline and solid lines are from early post adaptation. B) Results for initial subjects across all 3 conditions.

### PF Impulse

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Description automatically generatedPreliminary results from the first 5 participants are supportive of H2 (Figure 8). PF Impulse decreases following adaptation to cSBT and the Unilateral FastBrake. In contrast, it increases in the FastProp condition.

Figure 8: Left (fast side) PF Impulse

## Power Analysis

Given the planned statistical analysis via linear mixed effects models, power analysis was performed employing Monte Carlo simulation techniques(Landau and Stahl 2013) within R. Data was simulated based on estimates derived from the mean and standard deviations of the 5 preliminary participants (Table 3). Random samples of varying sizes were drawn from this simulated data and analyzed via the planned statistical methods. 500 simulations were performed across a range of sample sizes to determine the smallest sample for which at least 80% of simulations resulted in successful statistical outcomes.

Table 3: Assumptions used for power analysis in study 2

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Assumptions for Simulating Variables for Power Analysis** | | | | | |
|  |  |  |  |  |  |
|  |  | ***Step Length Ratio (H1)*** | | ***Fast Side PF Impulse (H2)*** | |
|  |  | **Baseline** | **Post Adaptation** | **Baseline** | **Post Adaptation** |
| cSBT | mean | 1.00 | 1.49 | 0.40 | 0.32 |
| sd | 0.05 | 0.32 | 0.04 | 0.04 |
| FastBrake | mean | 1.00 | 1.31 | 0.40 | 0.30 |
| sd | 0.05 | 0.32 | 0.04 | 0.04 |
| FastProp | mean | 1.00 | 1.26 | 0.40 | 0.44 |
| sd | 0.05 | 0.32 | 0.04 | 0.04 |

14 and 17 participants are required to achieve 80% power for (H1) and (H2), respectively. 20 participants will be included to provide an additional margin of safety.

## Discussion

A conventional split belt treadmill (cSBT) creates two abnormal periods of double support: stepping onto a faster belt and stepping off of a faster belt. Phase Dependent Speed Variation (PDSV) is an attempt to decompose the cSBT task into two distinct perturbations that impose only one altered period of double support or the other.

The objective of this study is to identify the short-term adaptations to these distinct perturbations. We hypothesize that kinematic alterations such as the Step Length Ratio will be altered in a similar way to cSBT but that distinct kinetic adaptations will occur given the perturbations occur at distinct points in the gait cycle. The preliminary results from 5 participants are supportive of these hypotheses, and the observed effects suggests that significant statistical results can be achieved with a modest sample size (~20).

Changes in motor behavior observed following adaptation to a split belt treadmill walking are likely mediated by underlying cerebellar adaptations(Morton and Bastian 2006).

The FastProp version of PDSV may provide a way to induce spontaneous cerebellar-mediated increases in paretic plantarflexor torque while increasing relative step length on the paretic side. This approach could be particularly beneficial for those who have experienced a cortical stroke and take a longer step on the non-paretic side. Although this presentation is less common(Balasubramanian et al. 2007; Allen, Kautz, and Neptune 2011), PDSV may offer these individuals a more customized intervention compared to a cSBT that evokes short-term decreases in paretic plantarflexor torque.

For individuals in the more common grouping who take a longer step on the paretic side, the FastBrake version of PDSV may induce changes in step symmetry and ankle torque that are similar to a cSBT without injecting as large of a perturbation into the gait cycle. This may make training with PDSV FastProp more tolerable than a cSBT while evoking a similar therapeutic response.

### Limitations

The study examines short-term effects in a healthy population, which may not directly map to a clinical post-stroke population.

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