# Study 3: Characterize adaptations to bilateral Phase-Dependent Speed Variation in healthy subjects.

## Introduction

In elderly individuals, slower walking speeds are associated with an increased risk of falls (Bergen, Stevens, and Burns 2016) and death (Hardy et al. 2007). Decreases in walking speed with age can be predicted by increases in the metabolic cost of walking as individuals age(Schrack et al. 2012). One of the primary contributors to an increasing metabolic cost of walking as individuals age is the tendency to decrease ankle plantarflexion (PF) joint torques and increase hip joint torques throughout the gait cycle(Delabastita et al. 2021). This “proximal shift” in joint torques is one of the hallmarks of aging gait (DeVita and Hortobagyi 2000; Kerrigan et al. 1998; Silder, Heiderscheit, and Thelen 2008). An intervention capable of reversing this proximal shift by increasing PF torque during gait may cultivate a more efficient gait pattern that disrupts the trajectory of decreased walking economy, decreased walking speeds, and increased mortality.

While simply walking faster can increase ankle PF demands in older adults (Silder, Heiderscheit, and Thelen 2008), it does not specifically address the inefficient gait patterns at a person’s typical self-selected speed or the tendency of older adults adopt a faster cadence than younger adults at a given speed(Nagasaki et al. 1996), a strategy that reduces mechanical demands at the ankle at the expense of increased demands at the hip(Umberger and Martin 2007).

Walking on a Split Belt Treadmill (SBT) with belts moving at different speeds has been shown to evoke spontaneous adaptations in PF torque that persist temporarily when the belts return to matched speeds (Lauziare et al. 2014). These changes in PF torque correlate with the changes in step length(Lauziare et al. 2014) that are typically observed following adaptation to a SBT(Reisman, Block, and Bastian 2005; Reisman et al. 2007) and are driven by feedforward cerebellar control mechanisms (Morton and Bastian 2006).

By its nature, the SBT task is asymmetrical. Shorter steps on the slow-belt side correspond with smaller peak PF torque on the fast-belt side; longer steps on the fast-belt side correspond with larger peak PF torque on the slow-belt side.

In Study 2, we introduced Phase Dependent Speed Variation (PDSV) as a tool to decompose the perturbations of a conventional SBT (cSBT) into two distinct components:

1. FastBrake (stepping *onto* a faster belt): the leading limb generates braking force while it is *pushed toward* the slower moving trailing limb.
2. FastProp (stepping *off of* a faster belt): the trailing limb generates propulsive force while being *pulled away* from the slower leading limb.

This decomposition is achieved by varying the target belt speed based on event triggers associated with the vertical Ground Reaction Force (GRF) under each limb. FastBrake (or FastProp) can be implemented by detecting when a limb leaves the belt to begin swing, triggering the belt to speed up (or slow down); after the limb touches down and begins to bear more vertical GRF than the opposite limb, the belt will slow down (or speed up).

A graph of a diagram

Description automatically generated with medium confidenceUnlike a cSBT, these components can be applied bilaterally. For bilateral FastBrake, the leading limb is always pushed toward the trailing limb. In bilateral FastProp, the trailing limb is always pulled away from the leading limb. Example belt speed profiles of this are shown in Figure 9.

Figure 9: Example belt speed profiles. Note that during double support when one limb is in early stance the contralateral limb is in late stance, resulting in a disparity between belt speeds.

We expect that such a bilateral implementation will evoke changes in PF torque like those of study 2. Specifically, we hypothesize that bilateral FastBrake will result in adaptations that bilaterally decrease PF impulse and FastProp will result in a bilateral increase in PF impulse.

## Methods

The methods of Study 3 will parallel those of Study 2, with the data collection occurring on the same day with the same subjects. The two conditions associated with Study 3 will be randomized along with those of Study 2.

### 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 38.

### Protocol

Participants will complete 2 randomized trials (Bilateral FastBrake, Bilateral FastProp) as outlined in Table 1. These will be randomized along with three additional conditions as outlined in Study 2.

*Table 1: Randomly ordered trials in Study 3 (Study 2 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 |

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Description automatically generatedEach trial consists of 3 minutes baseline walking (1 m/s), 6 minutes perturbed walking, and 3 minutes post-adaptation (Figure 10). This protocol structure aligns with previous research demonstrating detectable changes in PF torque following Adaptation36. We employ a 2:1 speed ratio. In cSBT walking, this can be largely adapted to within approximately 25 strides 31. Given typical stride times are less than 1.5 seconds each39 , our 6-minute adaptation period should allow ample time for full adaptation, with 3 minutes sufficient for subsequent washout.

Figure 10: 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 40 during the final minute of Baseline and Adaptation. 60-second recordings will capture late baseline/early adaptation and late adaptation/early post-adaptation 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 belt speed changes based on force plate data: at swing initiation when GRF goes to zero and then again when the vertical GRF exceeds the contralateral 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. The resulting belt speed profile then becomes synchronized to the participant’s gait cycle and changes in real time to any alterations in cadence (Figure 9).

### Rationale for Target Belt Speeds

Healthy individuals walking at ≥1 m/s have a swing time of roughly one-third of a second 39, allowing a 1 m/s speed change during single limb stance when the belt speed acceleration is 3 m/s2. This allows for a roughly even distribution of fast and baseline speeds across the braking and propulsive phases of stance (Figure 9). The 2:1 speed ratio (1 m/s slow, 2 m/s fast) is well-tolerated in healthy individuals during cSBT walking31 and elicits detectable after-effects in ankle joint torque36.

### 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 progression41. Joint centers will be defined by malleoli markers (ankle) and functional calibration methods (hip and knee)38.

A graph with lines and numbers

Description automatically generatedJoint 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 to remove the time normalization.

Figure 11: Time normalized ankle torque across stance before and after Adaptation. Average of 5 steps for Participant 1

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. Secondary variables for Early and Late Adaptation will be similarly calculated.

### Primary Variable

**Ankle PF impulse during stance**. Left and right sides will be averaged. Values will be normalized to body weight; thus units will be N.m.s/BW.

### Secondary Variables

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).

### Hypothesis

(H1) *Ankle PF Impulse*: Main effect for Period and interaction effect for Condition and Period. FastProp will increase ankle PF impulse from Baseline to Post Adaptation, while FastBrake will decrease it.

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Description automatically generated with medium confidenceA graphical depiction of the expected outcomes on primary variables is shown in Figure 12.

Figure 12: Hypothesized effect of Bilateral PDSV conditions on ankle plantarflexor impulse.

These findings would suggest that bilateral PDSV can modulate PF impulse during symmetrical gait. This may be achieved via a similar cerebellar-mediated feedforward control mechanism that is responsible for gait adaptations when walking on a cSBT.

### 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. Mean PF impulse will be analyzed across Periods (Baseline and Post-Adaptation) and Conditions (Bilateral FastBrake, and Bilateral 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 each 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 in predicting mean PF impulse in the bilateral conditions.

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 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 have trouble with the speed settings suggesting that a more individualized set of parameters should be used.

## Preliminary Results

Data for 5 participants has been analyzed.

### Ankle Torque Profiles

Examining the time normalized joint torques averaged across all subjects suggests a consistent effect like the one observed in Subject 1 in Figure 11. Upon returning to a steady 1 m/s belt speed following adaptation to the bilateral FastBrake condition, subjects on average exhibit an increase in early stance net PF torque and a decrease in late stance PF torque (Figure 13). This Post Adaptation torque profile stands in contrast to the curve following bilateral FastProp where there is a more marked increase in net PF torque beginning in early stance and extending to approximately 75% of stance.

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Figure 13: Joint torque across stance, average across all participants

### Ankle Plantarflexor Impulse

In Figure 14, the mean PF impulse across measurement periods is shown for each participant. Following Bilateral FastBrake, the impulse decreases from 0.40 to .36 N.m.s/BW. The impulse increases following adaptation to Bilateral FastProp from 0.41 to 0.50 N.m.s/BW.

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Figure 14: Plantarflexor impulse across stance (average across sides for each participant). Dotted lines connect overall mean for each Condition-Period.

## 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. 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 4: Assumptions for power analysis in Study 3

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| --- | --- | --- | --- |
| **Assumptions for Simulating Meant Plantarflexor Impulse (N.m.s/BW)** | | | |
|  |  |  |  |
|  |  | **Baseline** | **Post Adaptation** |
| FastBrake | mean | 0.40 | 0.36 |
| sd | 0.04 | 0.04 |
| FastProp | mean | 0.40 | 0.50 |
| sd | 0.04 | 0.04 |

Based on the above and using the assumptions in Table 4. **16 subjects should be sufficient for 80% power**. For an additional margin of safety, 20 participants will be included.

## Discussion

The objective of this study is to identify the short-term effects of bilaterally applied Phase-Dependent Speed Variation (PDSV) in a young and healthy population. This technique attempts to decompose the perturbation of a conventional Split Belt Treadmill (cSBT) into two components: stepping onto a faster belt and stepping off a faster belt. As adaptation to a cSBT evokes spontaneous asymmetrical changes in plantarflexor (PF) torque (Lauziare et al. 2014), we expect that adaptation to symmetrically applied PDSV may similarly evoke bilateral decreases or increases in PF torque. The preliminary results of this study align with this expectation.

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