Factors Modulating the Generalization of Human Locomotor Adaptation

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Generalization in motor control is defined as the ability to carry over information from trained experiences to novel situations. The generalization capacity is critical for the efficacy of robotic-assisted rehabilitation. Namely, if devices like exoskeletons or treadmills are to be used as training devices, patients must generalize the movements learned with the devices to real-life situations without them. Therefore, there is an interest in finding factors facilitating the generalization of corrected movements on a training device beyond the clinical setting. My dissertation focuses on identifying factors regulating the generalization process in locomotor adaptation. To this end, I used a split-belt treadmill (training context) to induce locomotor adaption by moving the legs at different speeds, and I evaluated the generalization of the treadmill-adaptation effects (after-effects) to overground walking (testing context). I specifically determined the extent to which small vs. large perturbations during split-belt walking have a distinct effect on the generalization of adapted movements in young and older adults (Aim 1). I found that older adults generalize their movements more than young regardless of the perturbation size experienced during adaptation. I also investigated the impact of increasing the extent of treadmill-adaptation vs. reducing the contextual similarity between the treadmill and overground walking on the generalization of locomotor adaptation (Aim 2). Results from this aim showed that contextual similarity is more important than the extent of adaptation in the generalization of corrected movements. Thus, in my last aim I used a pair of motorized shoes to induce split-belt treadmill-like adaptation that could increase the contextual similarity between walking with the motorized shoes (training context) and walking without them (testing context) (Aim 3). Results from Aim 3 confirmed that a pair of motorized shoes can induce the same type of robust locomotor adaptation as the split-belt treadmill, opening the possibility to enhance the generalization of correct movements with this training device to walking without it. Taken together, my work advanced our understanding of generalization in locomotor adaptation and has the potential to guide

training strategies exploiting the human generalization ability to benefit motor performances in new situations.

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Preface

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I dedicate this dissertation to:

My parents, Farrah and Hassan, who bore me, raised me, supported me, taught me, and loved me.

1.0 Introduction

The generalization of adapted movements from training to testing contexts is an important aspect of motor adaptation, which is a short-time scale form of motor learning. Generalization is defined as the ability to carry over information from trained experiences to novel situations (Krakauer, 2009; Torres-Oviedo et al., 2011). For example, an expert tennis player can generalize their motor repertoire to learn faster table tennis than someone without tennis experience. Thus, one can exploit generalization to benefit motor performances in new situations. This generalization capacity is critical for the efficacy of robotic-assisted rehabilitation. Namely, if devices like exoskeletons or treadmills are to be used as training devices, patients must generalize the movements learned on the devices to real-life situations without them. Therefore, there is an interest in finding factors facilitating the generalization of corrected movements beyond the clinical setting. The central hypothesis of this dissertation is that generalization in locomotor adaptation depends on age (i.e., old vs young), perturbation size (i.e., small vs. large errors), the extent of adaptation, and the similarity between training and testing conditions.

1.1 Specific Aims

1.1.1 Aim 1. Investigate the Extent to which Small vs. Large Errors can Regulate the Generalization of Locomotor Adaptation in Young and Older Adults

Effective interventions must induce motor after-effects that generalize to contexts other than the training context (e.g. motor patterns recalibrated on the treadmill must generalize to overground walking) that are applicable in all ages. Thus, it is important to understand age-related changes in the generalization of movements from training to real-life settings. Previous studies have shown that older adults generalize their movements more than young individuals (Fernández-Ruiz et al., 2000; Sombric et al., 2017; Sombric and Torres-Oviedo, 2021). However, the adaptation effects (i.e., aftereffects) in the training environment (e.g., treadmill walking) remain significantly larger in the training environment (e.g., treadmill walking) compared to those in a different environment (e.g., regular overground walking) (Reisman et al., 2009; Sombric et al., 2017; Sombric and Torres-Oviedo, 2021). This raises the question of whether the adaptation experience in older adults could be manipulated to increase the generalization of adapted movements. For example, small perturbations (i.e., gradual adaptation) of reaching (Kluzik et al., 2008) and walking (Torres-Oviedo and Bastian, 2012) in young adults and post-stroke individuals (Alcântara et al., 2018) result in a larger generalization of movements. It is, however, unknown whether a similar effect can be observed in older adults. I hypothesized that smaller error would lead to greater generalization and this difference would be augmented in older adults. Aim 1 will determine the extent to which small vs. large perturbation sizes can regulate the generalization of locomotor adaptation in young and older adults.

1.1.2 Aim 2. Investigate the Impact of the Extent of Adaptation and the Contextual Similarity on the Generalization of Locomotor Learning

There are other factors than age and perturbation size that can influence the generalization of movements from the training to the testing context. For example, it has been shown that one can increase the extent of adapted movements to induce greater generalization in the reaching movements (Hewitson et al., 2020). We also know that incline split-belt treadmill walking would lead to a greater extent of adaptation in both young (Sombric et al., 2019) and post-stroke patients (Sombric and Torres-Oviedo, 2020). While incline walking can improve locomotor adaptation, it decreases the contextual similarity between the incline treadmill and flat overground walking, since the forces that one needs to produce under these two conditions are different (Lay et al., 2006, 2007). The previous works of literature reported that decreasing contextual similarity would lead to poor generalization (Ahmed et al., 2008; Ingram et al., 2010; Torres-Oviedo and Bastian, 2010; Hirashima and Nozaki, 2012) while increasing contextual similarity enhances generalization (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). To this end, we do not know if increasing the extent of adaptation by augmenting the contextual similarity (i.e., inclining the treadmill) would increase the generalization of adapted movements from split-belt treadmill to overground walking. I hypothesized that increasing the extent of sensorimotor adaptation would lead to greater generalization despite the differences between the training and the testing environment. Aim 2 will investigate the impact of the extent of adaptation (favoring generalization) and contextual similarity (limiting generalization) on the generalization of locomotor adaptation.

1.1.3 Aim 3. Determine the Feasibility of Inducing a Speed Difference Between the Feet Using a Pair of Motorized Shoes to Result in Gait Adaptation Similar to Split-belt Treadmill

Most of the motor adaptation studies (Krakauer et al., 2000; Savin et al., 2010; Shadmehr and Mussa-ivaldi, 1994) and training (Lewek et al., 2018; Reisman et al., 2013) have to occur in the laboratory setting, which leads to task constraints that limit our ability to investigate factors that are critical for generalization outside the laboratory settings. Therefore, there could be more generalization of laboratory-based knowledge to realistic situations when the tasks studied in the laboratory are more similar to those observed under naturalistic conditions. To further investigate the importance of contextual similarity (i.e., the similarity between training and testing contexts) on the generalization of locomotor adaptation, I used a pair of motorized shoes that could increase the similarity between walking with the device (training context) and walking without it (testing context). I hypothesize that introducing a speed difference between participants' feet with the pair of motorized shoes that can improve the contextual similarity between the training and the testing setting would result in the adaptation of spatiotemporal gait patterns similar to split-belt walking. These motorized shoes can be used to induce motor adaptation in a more naturalistic environment that can perhaps lead to greater generalization of movements from the training to real-life situations. Aim 3 will determine how feasible is to use this device (i.e., a pair of motorized shoes) to induce gait adaptation similar to the split-belt treadmill.

1.2 Summary of Chapters

This dissertation includes 5 chapters. Chapter 1 is an introduction to the specific aims of the dissertation. Chapter 2 presents a draft of the study determining the extent to which small vs. large errors can regulate the generalization of locomotor adaptation in young and older adults (Aim 1). Chapter 3 includes a draft of the study determining the impact of the extent of adaptation and contextual similarity on the generalization of locomotor learning (Aim 2). Chapter 4 contains published work looking at the effect of inducing a speed difference between the feet using a pair of motorized shoes to result in adaptation of spatiotemporal gait patterns similar to split-belt treadmill (Aim 3). Chapter 5 summarizes the key findings and implications of Chapters 2-4.

2.0 Specific Aim 1 Older Adults Generalize their Movements Across Walking Contexts more than Young During Gradual and Abrupt Split-belt Walking

This work is presented as a draft.

2.1 Introduction

As the world's population grows older (Ortman et al., 2014), understanding how mechanisms of motor adaptation change with healthy aging, and how to counteract these age-related changes, becomes increasingly more important. Healthy older adults wish to maintain an independent (and active) lifestyle despite changes in their bodies or their surroundings (Nelson et al., 2007). For older adults to continue performing daily activities, they must maintain a flexible motor system that counteracts endogenous or exogenous perturbations to their movements through motor adaptation (King et al., 2013). Thus, it is important to understand age-related changes in motor adaptation. It has been shown that healthy aging impairs the rate of adaptation (Fernández-Ruiz et al., 2000; Sombric et al., 2017) and the extent of adapted movements (McNay and Willingham, 1998) when a novel environment is suddenly experienced. This seems to be a general trait of the aged motor system as it has been observed during reaching (Buch et al., 2003; Bock, 2005) and walking movements (Bruijn et al., 2012; Sombric et al., 2017). Age-related decline in adaptation performance could be attributed to impaired cognitive strategies. Specifically, older adults have difficulties identifying the external disturbances altering their movements (Buch et al., 2003; Bock, 2005; Hegele and Heuer, 2010; Heuer and Hegele, 2008), challenging their ability to consciously counteract them (Hegele and Heuer, 2013; Vandevoorde and de Xivry, 2020). On the other hand, there is no consensus on the impact of healthy aging on implicit processes underlying sensorimotor adaptation (Sülzenbrück and Heuer, 2009; Heuer and Hegele, 2009; Taylor and Ivry, 2011; Mazzoni and Krakauer, 2006), some suggest that this is preserved with healthy aging (Heuer and Hegele, 2008; Vandevoorde and de Xivry, 2020), whereas some others have shown age-releted decline in implicit motor adaptation (Wolpe et al., 2016; Iturralde and Torres-Oviedo, 2019). Thus, we investigated the extent to which small perturbations recruiting implicit processes (Roemmich and Bastian, 2015) would enhance the motor adaptation capacity in older individuals.

The generalization of adapted movements from training to testing contexts is an important aspect of motor adaptation. Namely, generalization is defined as the ability to carry over information from trained experiences to novel situations (Krakauer, 2009; Torres-Oviedo et al., 2011). For example, an expert tennis player can generalize their motor repertoire to learn faster table tennis than someone without tennis experience. Thus, one can exploit generalization to benefit motor performances in new situations. This generalization capacity is critical for the efficacy of robotic-assisted rehabilitation. Namely, if devices like exoskeletons or treadmills are to be used as training devices, patients must generalize the movements learned on the devices to real-life situations without them. Therefore, there is an interest in finding factors facilitating the generalization of corrected movements beyond the clinical setting. Previous studies have shown that older adults generalize their movements more than young individuals (Fernández-Ruiz et al., 2000; Sombric et al., 2017). However, the adaptation effects (i.e., aftereffects) remain significantly larger in the training environment (e.g., treadmill walking) compared to those in a different environment (e.g., regular overground walking) (Reisman et al., 2009; Sombric et al., 2017; Sombric and Torres-Oviedo, 2020). This raises the question of whether the adaptation experience in older adults could be manipulated to increase the generalization of adapted movements. For example, small perturbations (i.e., gradual adaptation) of reaching (**?**) and walking (Torres-Oviedo and Bastian, 2012) in young adults and clinical populations (Alcântara et al., 2018) results in a larger generalization of movements. It is, however, unknown whether a similar effect can be observed in older adults.

In this study, we investigated the extent to which small vs. large perturbations can regulate the generalization of locomotor adaptation in young and older adults. We hypothesized that gradual adaptation (i.e., small perturbations) would lead to more generalization in both age groups compared to abrupt adaptation (i.e., large perturbations). To test this hypothesis, young and older adults adapted their walking pattern on a split-belt treadmill either gradually or abruptly. We compared the adaptation and generalization of movements across these groups. Interestingly, older adults generalized more than young, regardless of the perturbation schedule, suggesting that healthy aging affects the motor capacity to contextualize motor memories in older populations.

2.2 Methods

2.2.1 Participants

We investigated if adaptation experience could be manipulated to increase the generalization of movements from the split-belt treadmill to overground in older adults. To this end, we adapted 32 healthy adults on a split-belt treadmill either gradually (i.e., small perturbations) or abruptly (i.e., large perturbations). Sixteen older (10 males and 6 females, mean age 75.9±4.8 years) and sixteen young participants (8 males and 8 females, mean age 24.7±5.9 years) experienced an abrupt or gradual perturbation. Older and young participants were randomly assigned to either perturbation group, yielding four groups of 8 participants each (i.e., $\text{Old}_{\text{Abrupt}}$, $\text{Old}_{\text{Gradual}}$ $\text{Young}_{\text{Abrupt}}$, $\text{Young}_{\text{Gradual}}$). Participants did not have sensory, neurological, or musculoskeletal disorders. The Institutional Review Board at the University of Pittsburgh approved the experimental protocol and all participants gave informed consent before testing.

2.2.2 Locomotor Paradigm

All participants walked both overground and on a treadmill during the experiment to complete a conventional generalization protocol that consists of three walking epochs: baseline, adaptation, and post-adaptation (Figure 1A-top). First, participants experienced the baseline epoch overground, during which they walked back-and-forth on a 9 m walkway (i.e., overground walking) for 6 minutes ($\sim$ 150 strides) before walking on the treadmill. Then, participants experienced the baseline epoch on the treadmill, during which they walked on the treadmill for three different speeds, which were slow (0.5 m/s), fast (1 m/s), and medium

(0.75 m/s) for 150 strides each. Next, participants experienced either an abrupt or gradual split-belt adaptation epoch for 600 strides. For the abrupt groups only, participants took a short (∼ 3 min) break after every 150 strides to allow older participants to rest. Participants in the gradual group did not take breaks because we wanted to avoid the errors that older adults experience after a break (Sombric et al., 2017). Besides, gradual adaptation did not require as many breaks because it was less strenuous than abrupt adaptation. Speed profiles for each error size are shown in (Figure 1A-bottom). In the abrupt case, the belts suddenly moved at a 2:1 belt ratio (1 and 0.5m/s), whereas in the gradual case, one belt sped up from 0.75 to 1m/s as the other one slowed down from 0.75 to 0.5 m/s. The faster belt was under the dominant leg for every participant, which was determined by self-report of preferred kicking leg (Kramer and Balsor, 1990). A brief catch condition (10 strides) during which both belts moved at 0.75 m/s was used to assess treadmill aftereffects. We chose this speed because it is approximately the effective speed at which participants walk during the adaptation epoch. Following the catch condition, participants were re-adapted to the split-belt perturbation for 300 strides (before walking overground). Lastly, in the post-adaptation epoch, participants walked overground, immediately after the re-adaptation period, for 6 minutes to assess the generalization of treadmill aftereffects to a different walking condition. Participants did not take any transition steps between walking on the treadmill and walking overground. Following the overground walking, participants walked again on the treadmill for 300 strides when the two belts moved at 0.75 m/s to assess the remaining aftereffects that were specific to the treadmill context.

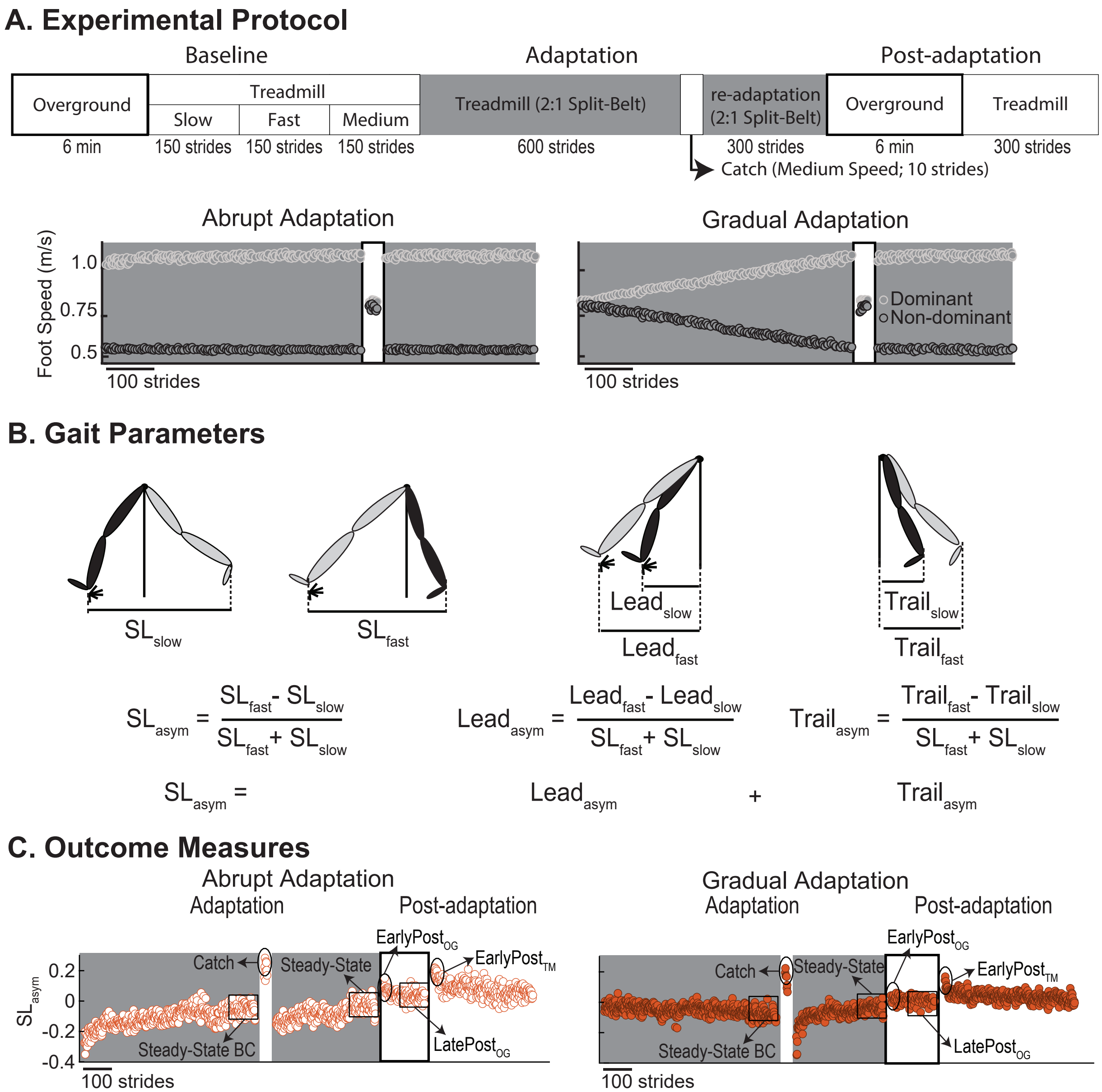


Figure 1: (A-top) Experimental protocol. The paradigm used for all groups consisted of 3 phases: baseline, adaptation, and post-adaptation. Thick black outlines represent overground walking. Thin black outlines represent treadmill conditions with both belts moving at the same speed (i.e., tied). The gray background represents the adaptation and re-adaptation periods that the dominant leg is moving two times faster than the non-dominant leg (i.e., split). (A-bottom) Speed profiles during adaptation. The graph illustrates the time course of the foot speed at which the dominant (white circles) and non-dominant legs (black circles) walked during the adaptation period. (B) This schematic illustrates step length asymmetry and its decomposition into leading and trailing leg asymmetries. Step length asymmetry is quantified as the difference between fast and slow step lengths, normalized by stride length. The equation and decomposition are explained in detail in

the section “Materials and Methods” of this article. In brief, the asymmetry between the fast (gray) and the slow (black) leading leg’s positions contribute to step length asymmetry. Similarly, asymmetry in the trailing leg’s positions also contributes to step length asymmetry. (C) Outcome measures. Epochs of interest are illustrated over an example step length asymmetry time course. The shaded gray area represents the adaptation period when the feet move at different speeds (“split” walking), whereas white areas represent when the feet move at the same speed. Think black outline represents the overground condition.

For safety purposes, all individuals wore a ceiling-mounted harness during the entire paradigm that only provided support in the event of a fall. For the treadmill walking conditions, participants were alerted when the treadmill was about to start and stop, but were not informed about the speed of the belts. Participants were instructed to hold on to a handrail positioned in front of them at the beginning and end of each treadmill condition, but were encouraged to let go as soon as they felt comfortable walking with their arms unrestricted (as they did during overground walking). Participants were also instructed to look straight ahead while walking so that they would not be distracted by the motion of the belts, which has been shown to alter the generalization of movements (Mariscal et al., 2020). An examiner stood by to monitor compliance with these instructions. Also, a plastic divider was placed between the treadmill belts to ensure that participants could not step on the wrong belt when walking on the treadmill.

2.2.2.1 Data Collection Kinematic and kinetic data were collected at 100 Hz and 1000 Hz, respectively, using a passive motion capture system (Vicon Motion Systems, Oxford UK), and an instrumented split-belt treadmill (Bertec, Columbus OH). Positions from the ankle (lateral malleolus) and the hip (greater trochanter) were collected bilaterally. Markers were also placed asymmetrically on the shanks and thighs to differentiate between the legs. Gaps in raw kinematic data due to marker occlusion were filled by visual inspection of each participant in Vicon Nexus software. Ground reaction forces recorded by force plates under each treadmill belt were used to count in real-time the number of strides that participants walked on the treadmill. Following data collection, instances of heel-strikes (i.e. foot landing) and toe-offs (i.e., foot lifting) were identified using kinematic data. This was done to have equivalent event detection on the treadmill and overground as in previous generalization studies (Torres-Oviedo and Bastian, 2010, 2012; Sombric et al., 2017; Mariscal et al., 2020; Sombric and Torres-Oviedo, 2021). Custom MATLAB scripts were used to perform all data analysis.

2.2.3 Data Analysis

2.2.3.1 Gait Parameters We characterized the adaptation and generalization patterns of every group using step length asymmetry, which is a metric conventionally used to quantify adaptation and generalization of gait in split-belt protocols. Step length asymmetry (SL_{asym}) was defined as the difference between step lengths (SL, the distance between ankles) when taking a step with the leg walking slow vs. the leg walking fast (Eq. 2.1). A zero value of step length asymmetry indicated that both step lengths were equal and a positive value indicated that the step length of the fast (dominant) leg was longer than the slow (non-dominant) leg. We further decomposed step length asymmetry into asymmetries between the leading ($Lead_{asym}$) or trailing ($Trail_{asym}$) positions (Figure 1B) because these have been shown to generalize differently (Mariscal et al., 2020). $Lead_{asym}$ (Eq. 2.2) and $Trail_{asym}$ (Eq. 2.3) were calculated as follows:

$$SL_{asym} = \frac{SL_{fast} - SL_{slow}}{SL_{fast} + SL_{slow}} \tag{2.1}$$

$$Lead_{asym} = \frac{Lead_{fast} - Lead_{slow}}{SL_{fast} + SL_{slow}} \tag{2.2}$$

$$Trail_{asym} = \frac{Trail_{fast} - Trail_{slow}}{SL_{fast} + SL_{slow}} \tag{2.3}$$

In these equations, the leading leg's position ($Lead_{fast}$ or $Lead_{slow}$) was defined as the ankle's marker position in the sagittal plane of the leg in front of the body at heel-strike and the trailing leg's position ($\text{Trail}_{\text{fast}}$ or $\text{Trail}_{\text{slow}}$) was defined as that of the leg behind the body. Both positions are computed with respect to the body, which is defined as the averaged position of the two hip markers at heel-strike. Moreover, the leading leg's position $\text{Lead}_{\text{fast}}$ was the position of the fast leg when this was in front of the body at fast heel-strike, whereas $\text{Lead}_{\text{slow}}$ was the same but when the slow leg was the leading leg. By convention, positive $\text{Lead}_{\text{asym}}$ values indicated that the fast leg landed farther forward from the body compared to when the slow leg landed forward when taking a step. Similarly, the trailing leg's position $\text{Trail}_{\text{fast}}$ was the position of the fast leg when this was the trailing leg at slow heel strike and vice versa for $\text{Trail}_{\text{slow}}$. By convention, negative $\text{Trail}_{\text{asym}}$ values indicated that the fast leg was farther behind the body compared to when the slow leg was behind the body at the contralateral heel strike.

2.2.3.2 Outcome Measures One outcome measure was maximum error size. This was computed as the average of the first 5 steps of step length asymmetry, SL_{asym}, measured when the 2 belts were at their maximum speed difference (i.e., Full split). The full split occurs at the beginning of the adaptation period for the abrupt groups whereas it happens at the beginning of the re-adaptation period (after the catch) for the gradual groups. We quantified the maximum error size by averaging the SL_{asym} during the first 5 strides of the full split period. We chose SL_{asym} as a global measure of error size since this is a performance metric that is robustly minimized as people adapt during split-belt adaptation paradigms (Reisman et al., 2005; Finley et al., 2015).

Six other outcome measures were computed for each gait parameter at specific epochs of interest within the experimental protocol. These outcome measures consisted of 1) steady-state before the catch, 2) aftereffects during the catch, 3) steady-state before overground walking, 4) early aftereffects overground, 5) late aftereffects overground, and 6) remaining aftereffects on the treadmill. These outcome measures were used to compare the adaptation and generalization between the groups (Figure 1C). In all outcome measures, we first removed the five strides at the end of each epoch to eliminate the effect of slowing down before stopping.

We quantified the steady-state before catch (SteadyStateBC, average of last 40 strides) to contrast the adapted states across groups before measuring the aftereffects on the treadmill during the catch. Next, we quantified the aftereffects during the catch period (Catch, average of the first 5 strides) to assess the aftereffects on the treadmill (i.e., training environment). We also quantified the steady-state before overground walking (SteadyState, average of last 40 strides) to get information about the final adapted state of each of the groups before testing participants overground. Then, we quantified early aftereffects overground (EarlyPost$_{\mathrm{OG}}$, averaged of first 5 strides) during the initial steps of the post-adaptation epoch to assess the generalization of movements from the treadmill (i.e., training environment) to overground walking (i.e., testing environment). The purpose of analyzing the late aftereffects overground (LatePost$_{\mathrm{OG}}$, average of last 40 strides). This was done to verify that all participants returned to their baseline values overground before returning to the treadmill. Lastly, we looked at the magnitude of aftereffects on the treadmill (i.e., EarlyPost$_{\mathrm{TM}}$) to assess the remaining treadmill-specific motor patterns not washed out by walking overground. The data of one participant in the Young$_{\mathrm{Abrupt}}$ group during the treadmill post-adaptation epoch was not recorded due to technical difficulties. Therefore, this participant was excluded from the analysis of EarlyPost$_{\mathrm{TM}}$ only. We subtracted participant-specific biases on the treadmill or overground before aggregating the data of all individuals for group analyses. This was done by subtracting the baseline biases on the treadmill or overground that matched the specific walking condition. For example, we subtracted the Baseline bias of each participant measured on the treadmill from outcome measures recorded on the treadmill during adaptation and post-adaptation epochs.

Lastly, we quantified %Generalization, which is the magnitude of aftereffects overground for step length asymmetry SL$_{\mathrm{asym}}$ expressed as a percentage of treadmill aftereffects as shown below:

$$\%Generalization = \frac{EarlyPost_{OG}}{Catch} \tag{2.4}$$

In this equation, EarlyPost$_{\mathrm{OG}}$ refers to the unbiased SL$_{\mathrm{asym}}$ values during early post-adaptation overground, and Catch refers to the unbiased SL$_{\mathrm{asym}}$ values during the catch period. A metric of %Generalization was not computed for other gait parameters because this was not numerically stable, resulting in unrealistic values of %Generalization for the $\text{Lead}_{\text{asym}}$ and $\text{Trail}_{\text{asym}}$ parameters. As an alternative, we performed a regression analysis to determine the relationship between the leading and trailing positions for each leg ($\text{Lead}_{\text{fast}}$, $\text{Lead}_{\text{slow}}$, $\text{Trail}_{\text{fast}}$ and $\text{Trail}_{\text{slow}}$) during post-adaptation on the treadmill (i.e., Catch) and overground (i.e., $\text{EarlyPost}_{\text{OG}}$). This procedure is described in the statistical analysis section.

2.2.4 Statistical Analysis

2.2.4.1 Power Analysis The number of participants per group was determined using the overground aftereffects of step length asymmetry from old and young participants experiencing the same abrupt speed differences as in this study (Sombric et al., 2017). We specifically assumed the estimated error variance of 0.00097 and the estimated difference of 0.032 between the older and young groups, as in our prior study (Sombric et al., 2017). We also anticipated a difference of 0.05 in the generalization between the gradual and abrupt groups based on a previous gradual vs. abrupt adaptation study (Torres-Oviedo and Bastian, 2012). This led to the effect size of 0.513 and 0.8 for older vs. young and gradual vs. abrupt comparisons, respectively. Our power analysis indicated that n = 8 participants per group would allow us to detect the anticipated difference between the older and young groups with at least 80% power and a significance level of 0.05. This sample size would also enable us to detect the expected difference between gradual and abrupt groups with 99% power. Therefore, we adopted a target sample size of 8 participants per group, which is comparable to the number of participants in other studies assessing the generalization of locomotor adaptation in older adults (Sombric et al., 2017; Sombric and Torres-Oviedo, 2021).

2.2.4.2 Group Analysis We performed one-sample Kolmogorov–Smirnov tests to determine if each parameter (i.e., SL_{asym}, $\text{Lead}_{\text{asym}}$, and $\text{Trail}_{\text{asym}}$) was normally distributed in every epoch of interest (i.e. Steady-State BC, Catch, Steady-State, $\text{EarlyPost}_{\text{OG}}$, $\text{LatePost}_{\text{OG}}$, and $\text{EarlyPost}_{\text{TM}}$) in all 4 groups. We found that all parameters were normally distributed, thus we ran separate two-way ANOVAs to test the effects of age (i.e., older vs. young) and perturbation size (i.e., small vs. large) on each of our gait parameters. These two-way ANOVAs were performed on unbiased data (i.e., the condition-specific baseline was removed) to focus on changes that occurred beyond those due to distinct group biases. In case of a significant interaction effect, we performed post-hoc comparisons with Tukey corrections to identify differences between groups. A significance level of $\alpha = 0.05$ was used for the two-way ANOVAs tests. Also, we wanted to determine if aftereffects were significant and participants go back to baseline behavior at the end of post adaptation in each group. Therefore, we performed a one-sided one-sample t-test to determine whether Catch, $\text{EarlyPost}_{\text{OG}}$, $\text{LatePost}_{\text{OG}}$, and $\text{EarlyPost}_{\text{TM}}$ values were different from zero. We corrected for multiple comparisons using a Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995), as we have done before (Aucie et al., 2020), in which we corrected the significance threshold for each epoch by setting a false discovery rate of 5% (FDR correction). Consequently, a p-value < 0.044 was significant considering the FDR correction. Stata (StataCorp., Collage Station, TX, United States) was used to perform the ANOVAs and one-sample t-tests, whereas MATLAB (TheMathWorks, Inc., Natick, MA, United States) was used for all other analyses. P-values, F-values, and t-values are reported for all group analyses, whereas effect sizes (η^2 for two-way ANOVAs, and Cohen's d for unpaired t-test) were only reported when a significant effect size was found.

2.2.4.3 Individual Analysis Previous studies have shown that speed-specific baseline values are predictive of steady-state behavior in the leading and trailing leg positions both in healthy (Sombric et al., 2019) and post-stroke survivors (Sombric and Torres-Oviedo, 2020). Therefore, we wanted to verify whether the same relationship holds in our data. Thus, we performed linear regression analysis for each group separately to quantify the similarity between lead and trail leg positions across speed-specific baseline and late adaptation epochs. To confirm the previous finding, we tested the model y = m*x, where y is the predicted leg position (e.g., $\text{Lead}_{\text{fast}}$) during late adaptation and x is the leg position during baseline (Sombric et al., 2019; Sombric and Torres-Oviedo, 2020). These regressions were performed in data pooled by age or perturbation size if the group analysis revealed that either of these factors had a significant effect on the dependent variable (i.e., steady-state). For example, if we observed a significant age effect on the steady-states, we performed a regression per age group (e.g., $Young_{Abrupt}$ and $Young_{Gradual}$ pooled together and Old_{Abrupt} and $Old_{Gradual}$ pooled together).

Furthermore, we evaluated the relation between leg movements post-adaptation on the treadmill vs. those overground. Therefore, we performed two sets of linear regression analyses with the leading and trailing leg's positions for each group separately. We normalized these distances by stride length (i.e., SL_{fast} + SL_{slow}) to account for different step sizes. We specifically tested the model y = m*x+b, where y is the predicted leading or trailing leg's position overground during post-adaptation, x is the measured leading or trailing leg's position during the catch condition on the treadmill, and b is the y-intercept of the fitted line. Similar to our other regression analyses, we performed separate regressions of pooled data based on age or perturbation size if we found a significant effect of either factor on the overground aftereffects. For example, if we observed a significant age effect on overground aftereffects, we performed two regressions with data pooled by age.

2.2.4.4 Post-hoc Analysis We unexpectedly observed that the maximum error size was not significantly different between the gradual and abrupt groups. In particular, gradual groups experienced errors, as large as those in the abrupt groups, during the initial steps of the re-adaptation condition following the catch condition. Therefore, we eliminated the catch condition in two additional groups (n=8 each) of older adults (10 males 6 females, mean age 76±5 years) adapted gradually ($Old_{Gradual\_NC}$) or abruptly (Old_{Abrupt_NC}) without a catch. These participants simply experienced a resting break, rather than a catch condition. We compared the generalization between these two groups with significantly different error sizes upon gradual vs. abrupt adaptation (see Figure 2). More specifically, we used unpaired t-tests to compare the aftereffects between the two groups when either walking overground ($EarlyPost_{OG}$, $LatePost_{OG}$) or on the treadmill ($EarlyPost_{TM}$). Of note, one participant in the $Old_{Gradual\_NC}$ was excluded from the analysis because the ankle marker was not collected throughout post-adaptation epochs due to technical difficulties. Also, some participants (i.e., n=3 in $\text{Old}_{\text{Abrupt\_NC}}$ and n=5 in the $\text{Old}_{\text{Gradual\_NC}}$) were not naïve to split-belt walking, but they had more than 6 weeks between experimental sessions, reducing the potential effect of split-belt exposure on overground aftereffects (Sombric et al., 2017).

2.3 Results

2.3.1 Gradual Adaptation Led to Small Errors Only in the Absence of a Catch Period

We observed that participants in the gradual and abrupt groups had the same error size (maximum errors) throughout the split-belt condition. We compared the error size when the belts had reached the same speeds (i.e. 0.5 m/s for the slow belt and 1 m/s for the fast belt) in both adaptation conditions. We found that the error size was the same in all groups. This was indicated by no significant effects of age ($F_{age(1,28)} = 0.03$, $p_{age} = 0.86$), perturbation schedule ($F_{error(1,28)} = 0.07$, $p_{error} = 0.79$), or interaction ($F_{interaction(1,28)} = 0.85$, $p_{interaction} = 0.36$) on step length asymmetry SL_{asym} (Figure 2B). Only participants in the older gradual group without the catch (Oldgradual_{NC}; Figure 2C; filled purple dots) experienced a smaller error size during adaptation compared to the older abrupt groups without the catch (Oldabrupt_{NC}; Figure 2C; empty purple dots). This was indicated by the significant maximum error size difference between these groups (t = -3.83, p = 0.0021, d = -1.98) (Figure 2D). Thus, the gradual groups experienced smaller errors compared to the abrupt groups only in the absence of the catch period.

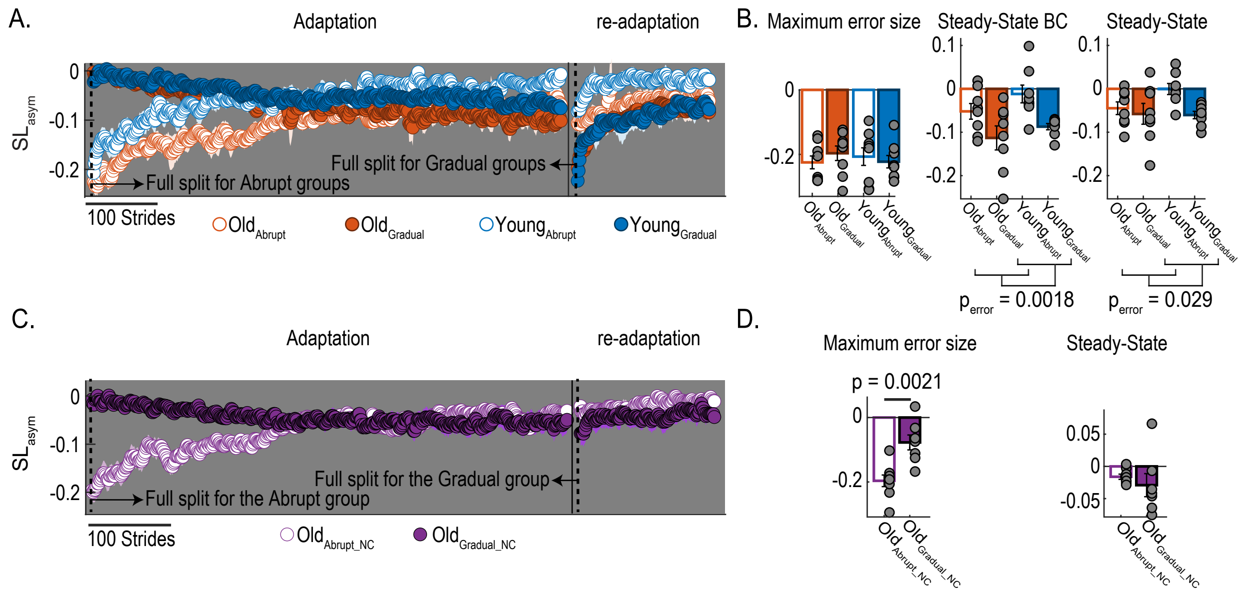


Figure 2: Timecourses of step length asymmetry (i.e., performance error) during the adaptation and re-adaptation periods. (A, C) Timecourses of step length asymmetry for all groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. The full split time point used to compute the maximum error size, for each group is indicated by the black dashed line. (B, D) Bar plots indicate the mean and standard errors for each group for the error size and steady-states. Gray dots represent values for individual participants. Note that the reported values are unbiased (i.e., bias in each participant during baseline on the treadmill was subtracted before calculating outcome measures).

2.3.2 Large Errors Led to a Higher Steady-state During Adaptation in all Age Groups

In general, we observed a significant effect of adaptation condition on the steady-state that people reached during split-belt walking. In other words, older and young participants corrected their step length asymmetry more when adapted abruptly compared to when adapted gradually. Figure 2A indicates the time course for SL_{asym} during adaptation and re-adaptation. Note that older and young participants adapted abruptly (i.e., empty dots) reached a steady-state closer to zero compared to those adapted gradually (i.e., filled dots) at the end of the adaptation (SteadyStateBC) and re-adaptation periods (SteadyState). Accordingly, there was a significant effect of adaptation condition on steady-state before the catch ($F_{error(1,28)} = 11.92$, $p_{error} = 0.0018$, $\eta^2 = 0.29$) and at the end of re-adaptation period ($F_{error(1,28)} = 5.34$, $p_{error} = 0.0285$, $\eta^2 = 0.16$) (Figure 2B); however, this effect was not observed in the absence of a catch period ($t = 0.76$; $p = 0.46$) (Figure 2D). Moreover, we did not find any age or interaction effect for SL_{asym} at steady-state before the catch ($F_{age(1,28)} = 2.79$, $p_{age} = 0.11$; $F_{interaction(1,28)} = 0.13$, $p_{interaction} = 0.72$) or at the end of re-adaptation period ($F_{age(1,28)} = 1.74$, $p_{age} = 0.19$; $F_{interaction(1,28)} = 2.17$, $p_{interaction} = 0.15$). In summary, the steady-state values of SL_{asym} were not affected by the participant's age but depended on the perturbation schedule during split-belt walking in the presence of a catch condition.

Furthermore, we observed that the steady-state differences in SL_{asym} across groups were driven by the asymmetry in the Leading legs (i.e., $Lead_{asym}$), but not by the asymmetry of trailing legs (i.e., $Trail_{asym}$). Figure 3A shows that $Lead_{asym}$ for older and young participants adapted gradually reached a smaller adapted state (Figure 3A; filled dots) than those adapted abruptly (Figure 3A; empty dots) at the end of both adaptation and re-adaptation periods (before and after the catch). On the other hand, $Trail_{asym}$ reached a similar adapted state across groups. Accordingly the $Lead_{asym}$ at steady-state before the catch ($F_{error(1,28)} = 14.03$, $p_{error} = 0.0008$, $\eta^2 = 0.33$) and at the end of adaptation ($F_{error(1,28)} = 5.81$, $p_{error} = 0.023$, $\eta^2 = 0.17$) was larger for older and young groups adapted gradually than those adapted abruptly (Figure 3B). For the $Trail_{asym}$ we observed an effect of adaptation type and age on the steady-state before catch ($F_{age(1,28)} = 4.22$, page $= 0.049$, $\eta^2 = 0.13$; $F_{error(1,28)} = 5.32$, $p_{error} = 0.028$, $\eta^2 = 0.16$), but these effects go away by the end of the re-adaptation period ($F_{age(1,28)} = 1.74$, page $= 0.19$; $F_{error(1,28)} = 1.56$, $p_{error} = 0.22$) (Figure 3D). Similar results were observed in the steady states of $Lead_{asym}$ and $Trail_{asym}$ when gradual and abrupt groups were adapted without a catch ($Lead_{asym}$: $t = 1.17$; $p = 0.26$; $Trail_{asym}$: $t = -0.14$; $p = 0.89$, data not shown). Therefore, all participants reached a similar trailing asymmetry at the end of the adaptation period, whereas the leading asymmetry was smaller at steady-state in the abrupt than gradual groups

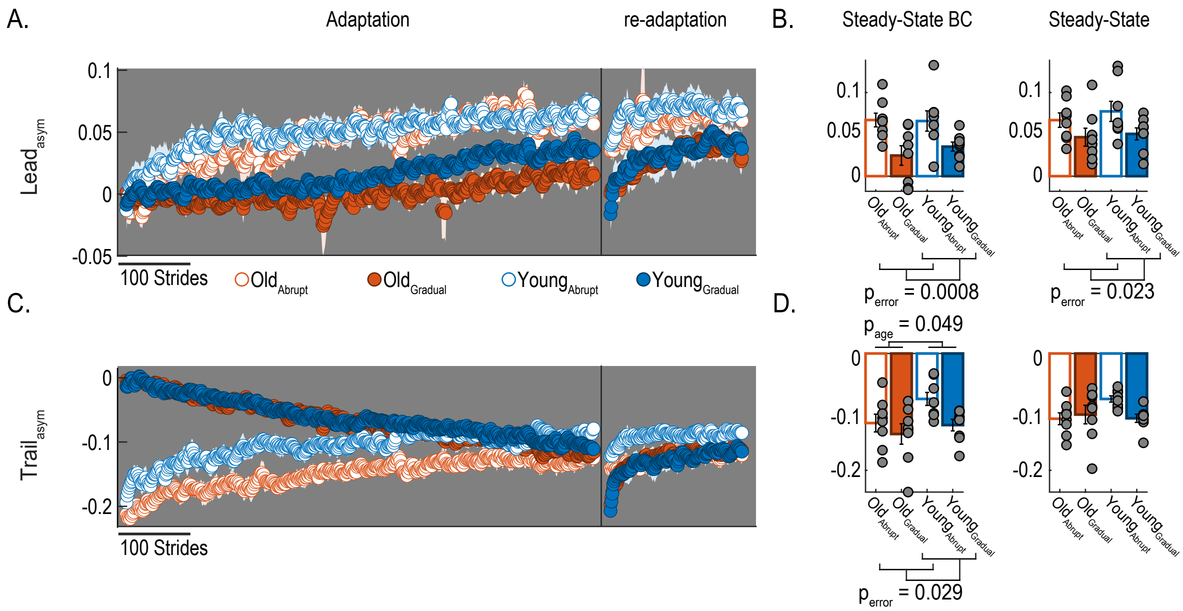


Figure 3: Adaptation of lead and trail asymmetries. (A, C) Time courses for lead and trail asymmetry during adaptation. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (B, D) Bar plots indicate the mean and standard errors for each group for steady-state before (i.e., Steady-State BC) and after (i.e., Steady-State) the catch. Gray dots represent individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking on the treadmill at the medium speed (i.e., 1 m/s).

2.3.3 Baseline Leg's Positions Predict the Steady-states Before and After the Catch in all Age Groups when Adapted Gradually or Abruptly

It has been shown recently that participants recover the baseline speed-specific, leading and trailing, leg's position during split-belt walking (Sombric et al., 2019; Sombric and Torres-Oviedo, 2020). We found that this relation between baseline and steady-state split-belt walking was not altered by age or perturbation size. This was indicated by the significant relationship between the speed-specific baseline and steady-states found in each of the four groups (Old_{Abrupt}, $Old_{Gradual}$, $Young_{Abrupt}$, and $Young_{Gradual}$) before ($R^2 > 0.63$; $p < 0.001$) and after the catch ($R^2 > 0.59$; $p < 0.001$). Also, our group analysis indicated that the perturbation scheduled affected the steady-state values of SL_{asym}. Thus, we grouped the participants by how they were adapted (Abruptly vs. Gradually). We found that the speed-specific baseline values were predictor of steady-state behavior both before (Abrupt: $R^2 = 0.86$; $p < 0.0001$ SS = 1.01*speed-specific baseline; Gradual: $R^2 = 0.82$; $p < 0.0001$ SS = 0.98*speed-specific baseline) and after the catch (Abrupt: $R^2 = 0.87$; $p < 0.0001$ SS = 1.01*speed-specific baseline; Gradual: $R^2 = 0.86$; $p < 0.0001$ SS = 0.98*speed-specific baseline) as shown in Figure 4. In sum, the steady-state movements in participants of all ages are strongly correlated to their baseline behavior, regardless of how the split-belt perturbation is introduced during the adaptation period.

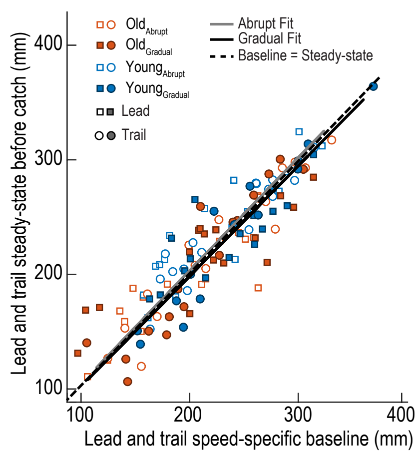


Figure 4: The similarity between lead and trailing leg's positions across speed-specific baseline and steady-state before catch epochs is illustrated by the significant regression of abrupt (y = m*x, 95% Confidence interval for m = [0.98, 1.04]) and gradual fits (y = m*x, 95% Confidence interval for m = [0.95, 1.01]). Note that the regression lines closely overlap with the idealized situation (dashed line) in which baseline and steady-state values are identical (dashed line; slope of one, i.e., y = x).

2.3.4 Abrupt Perturbations Result in Greater Aftereffects on the Treadmill in Young and Older Age Groups

Participants adapted gradually had smaller sensorimotor recalibration compared to those adapted abruptly regardless of age. This is indicated by the significantly smaller aftereffects during the catch period in the gradual (Figure 5A, filled circles) than abrupt groups (Figure 5A, empty circles). Figure 5A shows the averaged aftereffects during the catch condition on the treadmill for older and young participants adapted gradually or abruptly. Error size had a significant effect on the aftereffects during the catch for SL_{asym} ($F_{error(1,28)}$ = 20.31, p_{error} = 0.0001, η^2 = 0.42), $Lead_{asym}$ ($F_{error(1,28)}$ = 14.27, p = 0.0008, η^2 = 0.34), and $Trail_{asym}$ ($F_{error(1,28)}$ = 15.45, p = 0.0005, η^2 = 0.36). On the other hand, we did not have an age or interaction effect in any of the parameters during the catch (SL_{asym}: $F_{age(1,28)}$ = 3.72, p_{age} = 0.064; $F_{interaction(1,28)}$ = 0.38, $p_{interaction}$ = 0.54; $Lead_{asym}$: $F_{age(1,28)}$ = 2.45, p_{age} = 0.13; $F_{interaction(1,28)}$ = 0.64, $p_{interaction}$ = 0.43; $Trail_{asym}$: $F_{age(1,28)}$ = 2.99, p_{age} = 0.095; $F_{interaction(1,28)}$ = 0.07, $p_{interaction}$ = 0.79). Moreover, we observed a significant treadmill aftereffect for SL_{asym} and $Trail_{asym}$ in all the groups (See Table 1), but not in $Lead_{asym}$ for the $Old_{gradual}$ group, which is marginally significant (p = 0.057, t = 2.28) (Figure 5B). Overall, we observed that the perturbation schedule during adaptation, but not the participants' age, altered the aftereffects on the treadmill.

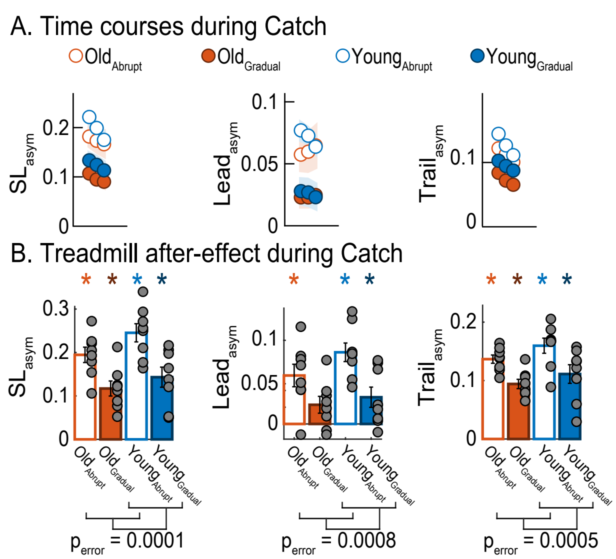


Figure 5: Treadmill aftereffect (i.e., Catch) for asymmetry parameters. (A) Timecourses for step length asymmetry, lead asymmetry, and trail asymmetry during the catch condition. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (B) Bar plots indicate the mean and standard errors for each group for the catch (i.e., Catch) condition. Gray dots represent individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking on the treadmill at medium speed (i.e., 1 m/s).

Table 1: Aftereffects during catch on the treadmill (Catch)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Old_{Abrupt}	<0.0001	10.9	3.89
$Old_{Gradual}$	0.0003	6.76	2.39
$Young_{Abrupt}$	<0.0001	11.7	4.14
$Young_{Gradual}$	0.0005	6.18	2.18
$Lead_{asym}$:			
Old_{Abrupt}	0.0035	4.31	1.52
$Old_{Gradual}$	0.057 (ns)	2.28	N/A
$Young_{Abrupt}$	0.0001	7.72	2.73
$Young_{Gradual}$	0.034	2.64	0.93
$Trail_{asym}$:			
Old_{Abrupt}	<0.0001	19.3	6.82
$Old_{Gradual}$	<0.0001	11.85	4.19
$Young_{Abrupt}$	<0.0001	12.33	4.36
$Young_{Gradual}$	0.0002	6.97	2.47

2.3.5 Older Participants Generalized more than Young When Adapted Gradually or Abruptly

We found that age had a significant effect on the generalization of locomotor adaptation. Figure 6 shows time courses of SL_{asym} during overground post-adaptation in groups experiencing a catch (Figure 6A) and those who did not (Figure 6B). While all groups exhibited initial aftereffects (i.e., $\text{EarlyPost}_{\text{OG}}$) that were significantly different from zero (See $\text{EarlyPost}_{\text{OG}}$ results in Table 2), older adults (i.e., orange and purple dots) have larger aftereffects when walking overground than young groups (i.e., blue dots). Accordingly, we found a significant effect of age on the initial overground aftereffects (i.e., $\text{EarlyPost}_{\text{OG}}$) for SL_{asym} in the groups experiencing a catch ($F_{\text{age}(1,28)} = 10.68$, $p_{\text{age}} = 0.0029$, $\eta^2 = 0.28$) (Figure 6C; $\text{Old}_{\text{Abrupt}}$, $\text{Old}_{\text{Gradual}}$, $\text{Young}_{\text{Abrupt}}$, and $\text{Young}_{\text{Gradual}}$). This age effect was also observed in %Generalization of SL_{asym} ($F_{\text{age}(1,28)} = 7.6$, $p_{\text{age}} = 0.01$, $\eta^2 = 0.21$), which quantifies the initial aftereffects overground (testing context) as a percentage of the initial aftereffects on the treadmill (training context).

Conversely, perturbation schedule did not impact the generalization of SL_{asym} quantified as raw values ($F_{\text{error}(1,28)} = 1.17$, $p_{\text{error}} = 0.29$; $F_{\text{interaction}(1,28)} < 0.001$, $p_{\text{interaction}} = 0.97$) or as a %Generalization ($F_{\text{error}(1,28)} = 3.46$, $p_{\text{error}} = 0.73$; $F_{\text{interaction}(1,28)} = 0.16$, $p_{\text{interaction}} = 0.69$). This finding was unexpected given previous reports indicating that gradual adaptation results in more overground aftereffects compared to abrupt adaptation (Torres-Oviedo and Bastian, 2012; Alcântara et al., 2018). We considered that the equally large errors between our gradual and abrupt groups experiencing a catch could explain the similar generalization across these perturbation schedules. Thus, we tested two additional groups of older adults who adapted gradually or abruptly without a catch ($\text{OldAbrupt}_{\text{NC}}$ and $\text{OldGradual}_{\text{NC}}$). The generalization patterns of these additional groups confirmed our finding that error size did not have an impact on the generalization of older adults. While these groups had significantly different error sizes during adaptation (Figure 2), they exhibit the same overground aftereffects ($t = 0.73$; $p = 0.48$) (Figure 6D). In sum, the participants' age, but not the perturbation schedule during adaptation, regulated the generalization of movements from the treadmill to overground.

The age-mediated differences in overground aftereffects vanished by the end of the post-adaptation period overground (i.e., $\text{LatePost}_{\text{OG}}$). Namely, we found that old and young groups maintained aftereffects that were significantly different from zero by the end of the post-adaptation period overground (See LatePost_{OG} results in Table 2). However, neither age, perturbation schedule, nor an interaction between these two factors had a significant effect on any of the asymmetry parameters at the end of the post-adaptation period (SL_{asym}: $F_{age(1,28)} = 0.62$, $p_{age} = 0.44$; $F_{error(1,28)} = 0.54$, $p_{error} = 0.47$; $F_{interaction(1,28)} = 0.34$, $p_{interaction} = 0.56$; $Lead_{asym}$: $F_{age(1,28)} = 0.33$, $p_{age} = 0.57$; $F_{error(1,28)} < 0.001$, $p_{error} = 0.95$; $F_{interaction(1,28)} = 0.02$, $p_{interaction} = 0.9$; $Trail_{asym}$: $F_{age(1,28)} = 0.59$, $p_{age} = 0.45$; $F_{error(1,28)} = 1.15$, $p_{error} = 0.29$; $F_{interaction(1,28)} = 0.64$, $p_{interaction} = 0.43$) (Figure 6C). Consistently, SL_{asym} values at the end of overground post-adaptation were similar between the older adults adapted abruptly or gradually without a catch (OldAbrupt_{NC} vs. OldGradual_{NC}; $t = -1.44$; $p = 0.17$) (Figure 6D). Therefore, while participants did not fully return to their baseline asymmetry values by the end of the post-adaptation period overground, neither age or perturbation schedule had an impact on the remaining aftereffects.

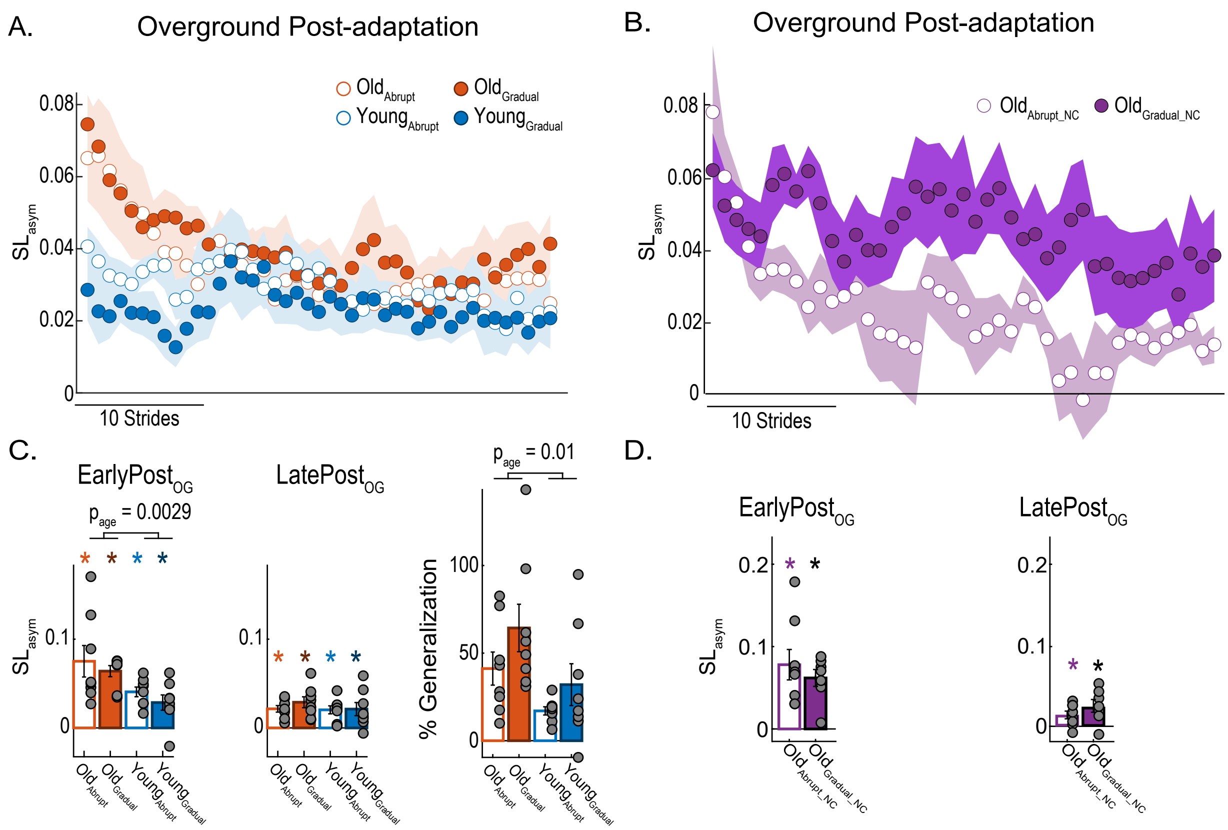


Figure 6: Generalization of step length asymmetry. (A-B) Time courses for step length asymmetry during overground walking post-adaptation for groups experiencing a catch condition (panel A) and groups without a catch (panel B). Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (C-D) Bar plots indicate the mean and standard errors for each group's initial ($EarlyPost_{OG}$) and final ($LatePost_{OG}$) aftereffects during overground post-adaptation. Group aftereffects are displayed for the groups experiencing a catch condition (panel C) and groups without a catch (panel D). (E) %Generalization for each group experiencing a catch condition. This measure indicates the size of initial aftereffects expressed as a percentage of the aftereffects on the treadmill during the catch. In all panels, gray dots represent individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking overground.

Similar results were observed in the other asymmetry measures: age had a significant effect on generalization of adapted movements, but perturbation type did not. All groups exhibited initial overground aftereffects that were significantly different from zero in $Trail_{asym}$ but not in $Lead_{asym}$ (See $EarlyPost_{OG}$ results in Table 2). Only the older participants adapted gradually without a catch ($Old_{Gradual\_NC}$ group) had significant overground aftereffects in all asymmetry measures including $Lead_{asym}$ ($p = 0.035$, $t = 2.72$, $d = 1.03$) (data not shown). Time courses are shown in figure 7A and 7B. We observed that older adults (i.e., orange dots) have larger aftereffects when walking overground than young groups (i.e., blue dots) in $Trail_{asym}$ but this effect was much smaller in $Lead_{asym}$. Accordingly, we found a significant effect of age on the initial overground aftereffects (i.e., $EarlyPost_{OG}$) of $Trail_{asym}$ ($F_{age(1,28)} = 9.53$, $p_{age} = 0.0045$, $\eta^2 = 0.25$) and $Lead_{asym}$, but the effect size was smaller in the latter one ($F_{age(1,28)} = 5.63$, $p_{age} = 0.025$, $\eta^2 = 0.17$). Interestingly, perturbation schedule did not impact the generalization of aftereffects in any parameter ($Lead_{asym}$: $F_{error(1,28)} = 1.38$, $p_{error} = 0.25$; $F_{interaction(1,28)} = 0.07$, $p_{interaction} = 0.79$; $Trail_{asym}$: $F_{error(1,28)} = 0.48$, $p_{error} = 0.49$; $F_{interaction(1,28)} = 0.09$, $p_{interaction} = 0.77$) contrasting our anticipated results. The age-mediated differences in overground aftereffects was not observed by the end of the post-adaptation period overground (i.e., $LatePost_{OG}$). Namely, while all groups exhibited significant aftereffects at the end of the post-adaptation period overground, except for Old_{Abrupt_NC} group ($p = 0.0821$, $t = 2.03$) in $Lead_{asym}$ (data not shown). However, neither age, perturbation schedule, nor an interaction between these two factors had a significant effect on the final aftereffects ($LatePost_{OG}$) for both asymmetry measures ($Lead_{asym}$: $F_{age(1,28)} = 0.33$, $p_{age} = 0.57$; $F_{error(1,28)} < 0.001$, $p_{error} = 0.95$; $F_{interaction(1,28)} = 0.02$, $p_{interaction} = 0.9$; $Trail_{asym}$: $F_{age(1,28)} = 0.59$, $p_{age} = 0.45$; $F_{error(1,28)} = 1.15$, $p_{error} = 0.29$; $F_{interaction(1,28)} = 0.64$, $p_{interaction} = 0.43$). In conclusion, older adults adapted gradually or abruptly generalized more than young the asymmetric pattern from the treadmill to overground walking.

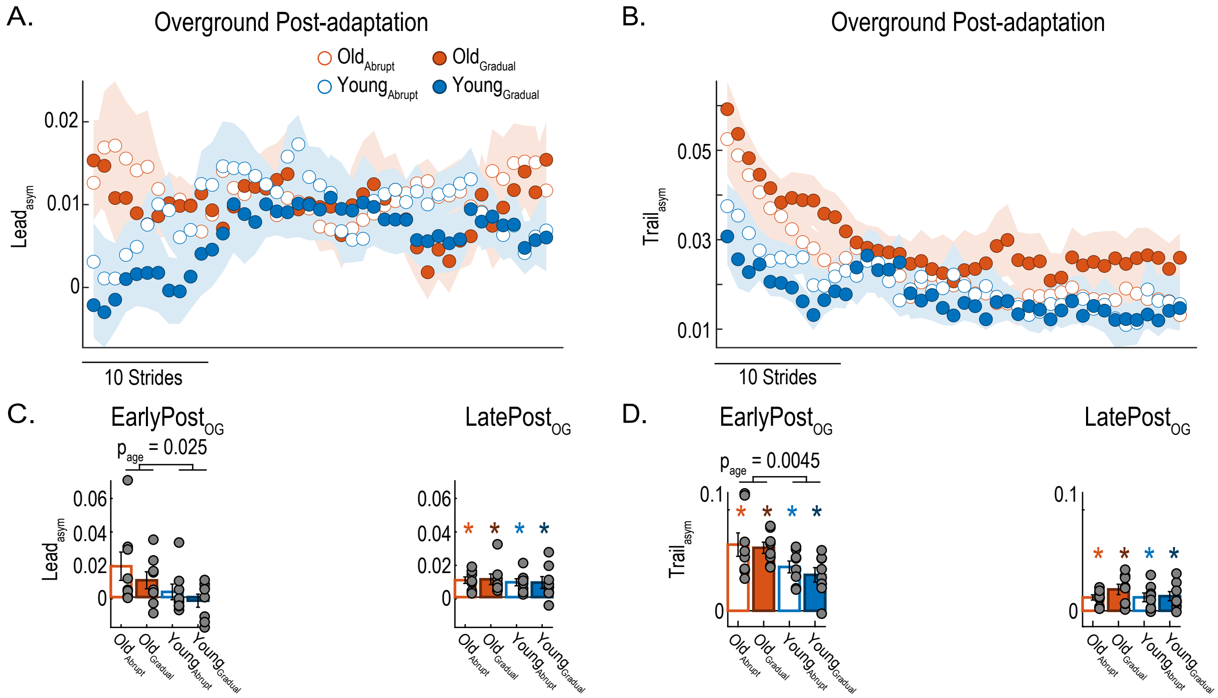


Figure 7: Overground aftereffects of lead asymmetry and trail asymmetry. (A-B) Time courses of the aftereffects in lead asymmetry and trail asymmetry during overground post-adaptation. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (C-D) Bar plots indicate the mean and standard errors for each group for the initial aftereffects (i.e., $\text{EarlyPost}_{\text{OG}}$) and final aftereffects (i.e., $\text{LatePost}_{\text{OG}}$) during the overground post-adaptation. Gray dots represent individual participants. Asterisks denote group averages significantly different from zero. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking overground.

Table 2: Aftereffects during overground post-adaptation

Initial aftereffects ($EarlyPost_{OG}$)			
Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Old_{Abrupt}	0.0039	4.24	1.49
$Old_{Gradual}$	<0.0001	10.2	3.62
$Young_{Abrupt}$	0.0001	7.43	2.63
$Young_{Gradual}$	0.013	3.33	1.18
Old_{Abrupt_NC}	0.0039	4.23	1.49
$Old_{Gradual\_NC}$	0.0009	6.02	2.28
$Lead_{asym}$:			
Old_{Abrupt}	0.066 (ns)	2.18	N/A
$Old_{Gradual}$	0.088 (ns)	1.98	N/A
$Young_{Abrupt}$	0.53 (ns)	0.66	N/A
$Young_{Gradual}$	0.60 (ns)	-0.55	N/A
Old_{Abrupt_NC}	0.14 (ns)	1.65	N/A
$Old_{Gradual\_NC}$	0.035	2.72	1.03
$Trail_{asym}$:			
Old_{Abrupt}	0.0008	5.65	1.99
$Old_{Gradual}$	<0.0001	11.15	3.94
$Young_{Abrupt}$	0.0001	7.41	2.62
$Young_{Gradual}$	0.0017	4.94	1.75
Old_{Abrupt_NC}	0.0003	6.54	2.31
$Old_{Gradual\_NC}$	0.0015	5.52	2.09

Table 2 (continued).

Final aftereffects ($LatePost_{OG}$)			
Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Old_{Abrupt}	0.0006	5.83	2.06
$Old_{Gradual}$	0.0022	4.72	1.67
$Young_{Abrupt}$	0.0027	4.53	1.60
$Young_{Gradual}$	0.024	2.87	1.01
Old_{Abrupt_NC}	0.022	2.94	1.04
$Old_{Gradual\_NC}$	0.014	3.42	1.29
$Lead_{asym}$:			
Old_{Abrupt}	0.0013	5.20	1.84
$Old_{Gradual}$	0.013	3.32	1.17
$Young_{Abrupt}$	0.004	4.21	1.49
$Young_{Gradual}$	0.044	2.46	0.87
Old_{Abrupt_NC}	0.082 (ns)	2.03	N/A
$Old_{Gradual\_NC}$	0.0061	4.14	1.56
$Trail_{asym}$:			
Old_{Abrupt}	0.0014	5.09	1.79
$Old_{Gradual}$	0.0046	4.09	1.45
$Young_{Abrupt}$	0.018	3.07	1.09
$Young_{Gradual}$	0.015	3.20	1.13
Old_{Abrupt_NC}	0.012	3.35	1.19
$Old_{Gradual\_NC}$	0.032	2.78	1.05

2.3.6 The Larger the Aftereffects in the Training Context, the Larger the Aftereffects in the Testing Context

Our regression analysis for each group revealed that the magnitude of aftereffects overground (testing context) is directly correlated to the magnitude of aftereffects in the (training context). This is indicated by the significant, positive correlations ($R^2 > 0.29$; $p < 0.031$) between each leg's position for the initial post-adaptation steps overground (Figure 8, y-axis) vs. the initial steps in the catch (Figure 8, x-axis). Only the Leading position of the slow leg ($Lead_{slow}$) and fast leg ($Lead_{fast}$) during the catch were not significantly correlated to those overground in the $Young_{Abrupt}$ group ($R^2 = 0.2$; $p = 0.08$). We further tested if the relation in the legs' positions across contexts was different between the young and older groups, given the significant age effect on the overground aftereffects in all asymmetry parameters. We found that the relation between the legs' positions across contexts was not different between the age groups in the leading leg (Older: $R^2 = 0.51$; $p < 0.0001$ $EarlyPost_{OG} = 0.4*Catch + 0.39$; Young: $R^2 = 0.17$; $p = 0.02$ $EarlyPost_{OG} = 0.21*Catch + 0.46$) and the trailing leg (Older: $R^2 = 0.73$; $p < 0.0001$ $EarlyPost_{OG} = 0.49*Catch + 0.16$; Young: $R^2 = 0.58$; $p < 0.0001$ EarlyPostOG = 0.31*Catch + 0.28). This was indicated by the overlapping confidence intervals in the regression parameters for the young group (Leading: slope=[0.38, 0.61], intercept=[0.10, 0.22]; Trailing: slope=[0.21, 0.40], intercept=[0.23, 0.33]) and old group (Leading: slope=[0.25, 0.55], intercept=[0.32, 0.46]; Trailing: slope=[0.036, 0.39], intercept=[0.37, 0.55]) (see overlapping shaded areas in Figure 8A and 8B). In sum, young and older participants exhibited a similar positive relationship between the leading and trailing legs' position across the treadmill and overground context.

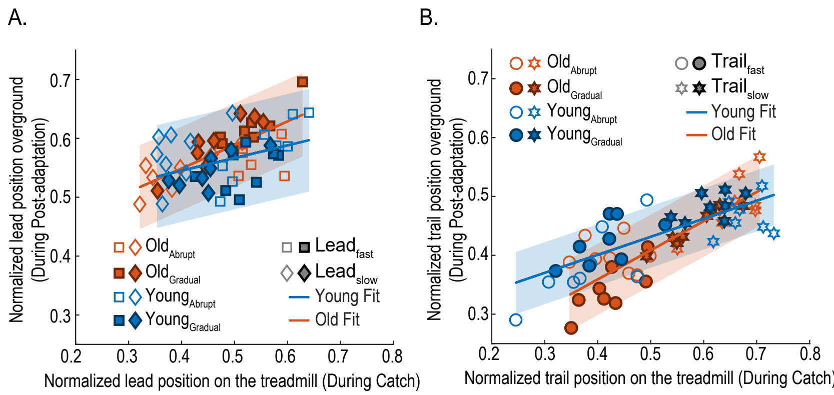


Figure 8: Relation between each leg's position in the initial steps ($\text{EarlyPost}_{\text{OG}}$) of overground post-adaptation and the initial steps on the treadmill during the catch (Catch). The values in the x and y axis indicate the leading and the trailing legs position during the aftereffects on the treadmill (i.e., Catch) and overground (i.e., $\text{EarlyPost}_{\text{OG}}$) as a percentage of stride length. (A) Scatter plot of each leg's leading position during the initial aftereffects measured during the catch on the treadmill (x-axis) and those measured overground (y-axis). We find a positive relation the aftereffects on the treadmill and those overground.

2.3.7 Overground Walking Washes out more the Treadmill Aftereffects in the Gradual than in the Abrupt Groups

We observed that perturbation scheduled affected the remaining aftereffects when participants returned to the treadmill after walking overground. Figure 9A, B, C, and D show the time courses of the remaining aftereffects during post-adaptation on the treadmill for all of the groups. We observed that all groups had aftereffects that were significantly different from zero in all asymmetry parameters (see Table 3). This was expected since participants did not return to their baseline gait before they walked again on the treadmill. However, young and older adults who adapted gradually (filled circles) had smaller remaining aftereffects than those who adapted abruptly (empty circles). This is clearly observed in the older adult groups adapted without a catch (purple dots). Consistently, the initial aftereffects during treadmill post-adaptation is significantly smaller in the $\text{Old}_{\text{gradual\_NC}}$ than in the $\text{Old}_{\text{abrupt\_NC}}$ groups ($t = 4.02$; $p = 0.0015$, $d = 2.08$). The groups adapted with a catch show a similar tendency. However, the effect of perturbation condition was only significant in the $Lead_{asym}$ ($F_{error(1,27)}$ = 4.68, p_{error} = 0.039, η^2 = 0.15) and not in SL_{asym} ($F_{error(1,27)}$ = 2.29, p_{error} = 0.14) or $Trail_{asym}$ ($F_{error(1,27)}$ = 0.57, p_{error} = 0.46). We also found that neither age (SL_{asym}: $F_{age(1,27)}$ = 0.39, p_{age} = 0.54; $Lead_{asym}$: $F_{age(1,27)}$ = 0.03, p_{age} = 0.87; $Trail_{asym}$: $F_{age(1,27)}$ = 0.88, p_{age} = 0.36) nor an interaction between age and perturbation schedule significantly modified the washout of treadmill aftereffects by overground walking (SL_{asym}: $F_{interaction(1,27)}$ = 0.04, $p_{interaction}$ = 0.84; $Lead_{asym}$: $F_{interaction(1,27)}$ = 0.01, $p_{interaction}$ = 0.93; $Trail_{asym}$: $F_{interaction(1,27)}$ = 0.08, $p_{interaction}$ = 0.78). In sum, overground walking washed out more the treadmill aftereffects when participants were adapted gradually than when they were adapted abruptly.

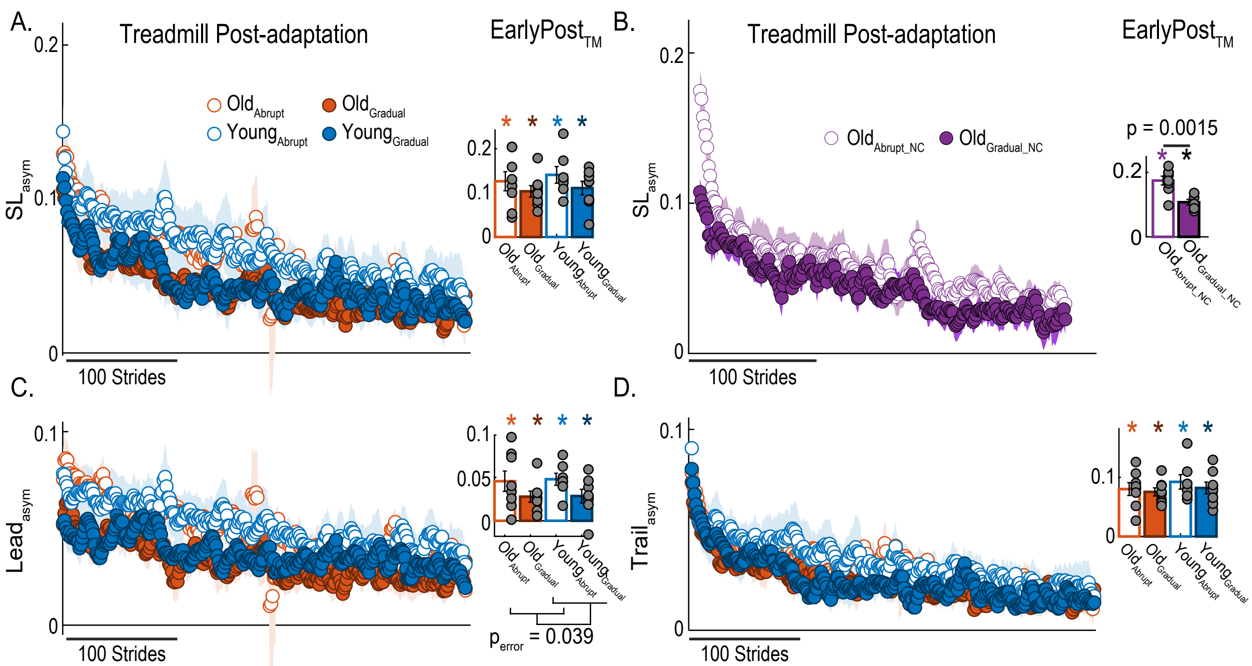


Figure 9: Aftereffects on the treadmill of all asymmetry parameters. (A-D -left side) Time courses for step length asymmetry when walking on the treadmill during post-adaptation for groups experiencing a catch condition (panel A) and groups without a catch (panel B). Time courses for lead asymmetry (panel C) and trail asymmetry (panel D) for the groups experiencing a catch are also shown. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (A-D -right side) Bar plots indicate the mean and standard errors for each group's initial aftereffects on the treadmill following overground walking. Gray dots represent individual participants. Asterisks denote group averages significantly different from zero. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking on the treadmill at the medium speed ((i.e., 1 m/s).

Table 3: Initial aftereffects during treadmill post-adaptation ($EarlyPost_{TM}$)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Old_{Abrupt}	0.0006	5.86	2.07
$Old_{Gradual}$	0.0001	7.97	2.82
$Young_{Abrupt}$	0.0003	7.49	2.83
$Young_{Gradual}$	0.0002	7.23	2.56
Old_{Abrupt_NC}	<0.0001	12.9	4.56
$Old_{Gradual\_NC}$	<0.0001	12.1	4.56
$Lead_{asym}$:			
Old_{Abrupt}	0.0059	3.90	1.38
$Old_{Gradual}$	0.0034	4.34	1.53
$Young_{Abrupt}$	0.0005	6.89	2.61
$Young_{Gradual}$	0.0083	3.64	1.29
Old_{Abrupt_NC}	0.0006	5.92	2.09
$Old_{Gradual\_NC}$	0.033	2.75	1.04
$Trail_{asym}$:			
Old_{Abrupt}	0.0002	7.38	2.61
$Old_{Gradual}$	<0.0001	11.01	3.89
$Young_{Abrupt}$	0.0003	7.55	2.85
$Young_{Gradual}$	0.0001	8.27	2.92
Old_{Abrupt_NC}	<0.0001	20.4	7.21
$Old_{Gradual\_NC}$	<0.0001	11.68	4.41

2.4 Discussion

We investigated the interaction between age and perturbation size, which are two factors known to influence the generalization of locomotor adaptation. We found that experiencing abrupt adaptation (large perturbation size) led to greater steady states and aftereffects on the treadmill compared to gradual adaptation (small perturbation size) in both age groups. On the other hand, we observed that older adults generalized their movements to overground walking more than young regardless of the perturbation size during adaptation. Our regression analysis revealed that the movements during baseline at different speeds predict the behavior of steady states for both age groups. We also found that individual leg movements, quantified by the leg's position of each leg, during overground post-adaptation can be predicted by the catch behavior on the treadmill. Lastly, we found that the overground walking following adaptation washes out the effect of gradual adaptation more than abrupt.

2.4.1 Large Errors Led to Higher Steady-states and Aftereffects on the Treadmill in Both Age Groups

Participants in the abrupt groups reached a higher steady-state compared to the gradual groups during the adaptation at the presence of catch in both young and older age groups. This means that large errors led to more adaptation of movements compared to small errors when the catch was present. On the other hand, in our post-hoc analysis (i.e., no catch trial), we found that both abrupt and gradual groups had the same steady-states. This finding is aligned with the fact that gradual adaptation leads to fragile motor memories (Roemmich and Bastian, 2015) and it is more susceptible to washout by the catch trial as observed in our groups with the catch. In other words, experiencing catch is similar to experiencing the perturbation in the opposite direction that could washout the fragile motor memories in the gradual groups. Another explanation is that the participants in the gradual groups with the catch experienced large errors during the re-adaptation phase as if they were adapted for the first time (Roemmich and Bastian, 2015); however, they adapted for a shorter period compared to the abrupt adaptation (300 strides vs. 900 strides). We know from reaching studies that a short exposure of the abrupt perturbation may not be enough to fully adapt the movement (Joiner et al., 2013). Therefore, it is possible that the re-adaptation period of 300 strides was not long enough to fully recover the adapted states in gradual groups with the catch, while in the case of no catch, participants got exposed to the same perturbation without any disruption, which helped them store the recalibrated movements easier.

We also observed that the participants in the abrupt groups have higher aftereffects on the treadmill (i.e., more sensorimotor recalibration) compared to the participants in the gradual groups in both young and older age groups. In other words, large errors led to more sensorimotor recalibration of movements within the same environment compared to small errors, which is consistent with previous findings (Torres-Oviedo and Bastian, 2012). Other locomotor adaptation studies have shown that an abrupt but not gradual change in the walking environment engages neural processes to acquire and store explicit knowledge about the new environment (Roemmich and Bastian, 2015). This fact can explain why the abrupt adaptation facilitated the storage of the recalibrated movements compared to the gradual adaptation (i.e., small errors). Moreover, the storage of the recalibrated movements is slower with the gradual than the abrupt perturbation (Taylor et al., 2014); therefore, our gradual groups may not be fully adapted by the end of the adaptation phase. Another explanation for the fact that the gradual and the abrupt perturbation led to different aftereffects, can be that they result in different internal representations of the learning environment (Roemmich and Bastian, 2015). For instance, in reaching literature, it has been shown that the adaptation to an abrupt perturbation is driven by feedforward motor planning, whereas adaptation to a gradual perturbation is dependent on feedback control (Saijo and Gomi, 2010).

While the perturbation schedule during adaptation altered the steady states and aftereffects on the treadmill, we did not find any effect of age in these epochs. This observation is consistent with previous studies showing that sensorimotor recalibration upon external perturbations is not impaired in older adults for walking (Bruijn et al., 2012; Malone and Bastian, 2016; Sombric et al., 2017) and reaching behaviors (Buch et al., 2003; Bock, 2005; Bock and Girgenrath, 2006) for the kinematic metrics. In contrast, our finding is not consistent with the previous literature on muscle activity. Iturralde and Torres-Oviedo's model showed that as age increases the adaptability of movements decreases (Iturralde and Torres-Oviedo, 2019) in the muscle domain. This suggests that the control of limb movements is affected by age at the muscle domain; however, those changes are not translated to the kinematic level of our movements as shown by our data. Taken together, the error size experienced during the adaptation plays a significant role in sensorimotor adaptation and recalibration while the age of participants is only affecting the muscle and not the kinematic domains.

2.4.2 Older Participants Generalized more than Young in Gradual and Abrupt Perturbations

We found that age had a significant effect on the generalization of locomotor adaptation, regardless of the error size experienced during adaptation. Previous studies have shown that older adults have a larger transfer of adapted movements across conditions in reaching (Fernández-Ruiz et al., 2000; Bock and Girgenrath, 2006; Heuer and Hegele, 2008) and walking (Sombric et al., 2017), which is consistent with our findings. In other words, older adults exhibit greater motor perseveration compared to younger adults when they switch across different environments. There are three potential explanations for these age-related differences. First, more motor perseveration in older adults can be explained by the degeneration of basal ganglia as we age. We know that the basal ganglia are responsible for motor switching (Brown and Almeida, 2011; Leunissen et al., 2013; Balser et al., 2014). This means that the age-related structural (Wolpe et al., 2020) and functional (Bäckman et al., 2006; Ota et al., 2006; Walhovd et al., 2011) changes in the basal ganglia can lead to poor motor switching and greater motor perseveration. Second, older adults might rely more on the movements that they have just learned during adaptation. Because healthy aging results in higher motor (Kallio et al., 2012; Vanden Noven et al., 2014) and sensory noise (Zhang et al., 2008; Goble et al., 2009; Maheu et al., 2015); therefore, they have less sensitivity to errors. This means that older adults try to generate the same pattern that they were doing at the end of adaptation instead of updating their movement (i.e., deadapting the learned movements) as they transition to the overground walking condition. Lastly, older adults are naturally more variable in their movements compared to young adults (Osoba et al., 2019). This means that older adults tend to attribute the sensed errors during adaptation to their own faulty movements (Berniker and Kording, 2008; Kelly and Sober, 2014); therefore, having difficulty switching their motor patterns across different conditions (Sombric et al., 2017; Sombric and Torres-Oviedo, 2021). Taken together, our results showed that older adults have a harder time switching and disengaging their motor patterns when facing a new environment compared to young adults.

On the other hand, we found that error size does not affect the generalization of movements from the treadmill (i.e., training environment) to the overground (i.e., testing environment). This is at odds with previous literature showing that gradual adaptation leads to more generalization than abrupt adaptation in both young adults (Torres-Oviedo and Bastian, 2012) and post-stroke patients (Alcântara et al., 2018). This discrepancy might be because our gradual groups did not adapt as much as our abrupt groups, which had not been reported before (Torres-Oviedo and Bastian, 2012; Alcântara et al., 2018). The reduced adaptation of our gradual groups compared to the abrupt is indicated by the lower steady-states, which is known to be positively correlated to less sensorimotor recalibration (i.e., less aftereffects on the treadmill) (Sombric et al., 2019; Aucie et al., 2020). This deficit in the adaptation of gradual groups compared to abrupt groups might have not been observed before because we used a smaller perturbation size (speed difference) than the one used before (Torres-Oviedo and Bastian, 2012; Alcântara et al., 2018). Smaller perturbation sizes are known to induce less adaptation and smaller aftereffects (Morehead et al., 2015; Marinovic et al., 2017; Finley et al., 2015; Yokoyama et al., 2018). Our interpretation is consistent with previous work showing that gradual adaptation results into more fragile motor memories than abrupt adaptation in the absence of an extended period of adaptation at the fully perturbed state (Roemmich and Bastian, 2015). Lastly, smaller aftereffects indicate less sensorimotor recalibration, but also make it more challenging to detect between group differences in generalization, which is a metric with large inter-subject variability. Taken together, our results suggest that the generalization of aftereffects beyond the training environment might be limited by the extent to which people adapt their movements in said training environment.

Another factor reducing the generalization of the gradual groups compared to the abrupt groups in those with the catch trial might have been the large asymmetries induce by the catch trial itself. Notably, the gradual groups experiencing the catch trial exhibited the same maximum error size as the abrupt groups before overground post-adaptation. Thus, participants in the gradual groups with the catch trial did not truly experience smaller errors than those in the abrupt groups. These large errors in the gradual groups could have been perceived as out-of-the ordinary, limiting the generalization of movements (Torres-Oviedo and Bastian, 2012). The catch trial could have also limited the generalization of movements because removing the perturbation during the catch is a perturbation in-and-of itself (Herzfeld et al., 2014; Iturralde and Torres-Oviedo, 2019), which is repeated when people walk overground. Thus, the repeated exposure to removing the split-perturbation might facilitate switching between distinct walking patterns within the training environment or across distinct walking environments. We are currently testing this hypothesis in another study explicitly assessing the impact of catch trials on the generalization of movements.

2.4.3 Speed Specific Baseline Positions are a Predictor of Steady-state Before and After the Catch regardless of the Error Size

We found that the speed-specific baseline values are a predictor of steady-state behavior both before and after the catch for both gradual and abrupt groups despite the differences during the steady states. This finding is consistent with previous literature showing that all participants recover their baseline leg orientation in both young healthy adults (Sombric et al., 2019) and post-stroke survivors (Sombric and Torres-Oviedo, 2020). We know that leg orientation is closely regulated to walk at distinct speeds (Orendurff et al., 2008). Therefore, participants need to take speed-specific step lengths to adapt to the split-belt environment. In other words, participants would match the speed-specific step length (i.e., biomechanically driven) by late adaptation regardless of their age or the error size that they are experiencing during the adaptation. This implies that neither participants' age nor the error size during adaptation can impact the biomechanical constrain set by the speed of the belts when walking on the treadmill.

While all groups recovered their baseline leg orientation at the steady-state at the individual level, we found that the error size impacted the steady states that participants reach in leading, but not trailing asymmetry measures regardless of age groups. We know from previous studies that the lead and trail asymmetry are correlated to spatial and temporal features of the gait, respectively (Mariscal et al., 2020; Sombric and Torres-Oviedo, 2020). Therefore, differences in the adaptation of lead and trail asymmetry can be explained by the fact that the spatial and temporal features of the gait adaptation are controlled by different neural substrates (Malone and Bastian, 2014) in post-stroke patients. This has also been reported in other split-belt paradigms (Bruijn et al., 2012; Vervoort et al., 2019) in older adults. In summary, our findings confirmed that the spatial and temporal gait features adapt differently, but are constrained to the speed at which the participant is walking at.

2.4.4 Overground Walking Washes out more the Treadmill Aftereffects in the Gradual than in the Abrupt Groups

We found that overground walking washed out more the treadmill aftereffects when participants were adapted gradually than when they were adapted abruptly. Specifically, we observed this in $\mathrm{Lead_{asym}}$ for the groups that experienced the catch trial. This is in odds with previous literature reporting no differences between the gradual and abrupt adaptation in the spatial domain ($\mathrm{Lead_{asym}}$ is correlated to the spatial domain) when the participants return to the training environment (Torres-Oviedo and Bastian, 2012). One interpretation is that overground walking only washed out the aftereffect in $\mathrm{SL_{asym}}$ and $\mathrm{Trail_{asym}}$ because these were the only adapted movement that carried over to overground walking and consequently, that was washout by overground walking. We did not observe any difference in the $\mathrm{SL_{asym}}$ and $\mathrm{Trail_{asym}}$. This observation was consistent with the previous literature showing no differences between the gradual and abrupt adaptation in $\mathrm{SL_{asym}}$ and temporal ($\mathrm{Trial_{asym}}$ is correlated to the temporal domain) measures (Torres-Oviedo and Bastian, 2012; Alcântara et al., 2018). On the other hand, we found that in the groups without the catch there is a difference between the gradual and the abrupt group even in $\mathrm{SL_{asym}}$. This means that gradual adaptation leads to fragile motor memories (Roemmich and Bastian, 2015), that is, motor memories that are susceptible to washout by walking in other contexts, which is particularly clear in the people walking without a catch. Another interpretation is that participants adapted more abruptly than gradually (Torres-Oviedo and Bastian, 2012; Roemmich and Bastian, 2015), thus, the remaining aftereffects have to be greater for the abrupt than the gradual condition for the same extent of washout by the overground experience. To sum up, gradual adaptation leads to motor memories that are more susceptible to washout by overground walking, and this susceptibility increases by introducing disruption during adaptation.

2.4.5 Clinical Implications

Our results confirmed that older adults have difficulties switching motor patterns (Fernández-Ruiz et al., 2000; Bock and Girgenrath, 2006; Heuer and Hegele, 2008; Sombric et al., 2017; Sombric and Torres-Oviedo, 2021), which leads to a higher risk of falls (Lockhart et al., 2002). Thus, the risk of falling in the older population could decrease by practicing switching between various walking terrains (Tinetti et al., 1996; Wagner et al., 1994). We also showed that healthy aging leads to larger generalization regardless of the error size experienced during adaptation. This is particularly important because our findings suggest that large errors might be better than small when training older populations. Specifically, we demonstrated that older adults learn more from large than small errors, and large errors do not limit the generalization of this learning. Therefore, the older clinical population will carry over the enhanced learning from large errors to real-life situations. Finally, the age-related differences in generalization also suggest that older patients have a higher chance of motor improvements beyond the clinical setting compared to younger ones. In conclusion, our work highlights the importance of age-related changes in the generalization of locomotor adaptation, which could be used to improve rehabilitation techniques beyond clinical settings.

3.0 Specific Aim 2 The Similarity Between the Training and the Testing Environments Favors the Generalization of Sensorimotor Adaptation more than the Adaptation itself in Split-belt Walking

This work is presented as a draft.

3.1 Introduction

The generalization of adapted movements from training to testing contexts is an important aspect of motor adaptation. Namely, generalization is defined as the ability to carry over movements from trained experiences when facing novel situations (Krakauer, 2009; Torres-Oviedo et al., 2011). For example, an expert tennis player can generalize their motor repertoire to learn table tennis faster than someone without tennis experience. Thus, one can exploit generalization to benefit motor performances in new situations. Also, increasing the generalization of learning could improve the efficacy of rehabilitation beyond the clinical setting. For instance, if devices like exoskeletons or treadmills (Dietz et al., 1994; Reisman et al., 2005) are to be used as training devices, patients must generalize the movements learned on the devices to real-life situations without them. Therefore, there is an interest in finding factors facilitating the generalization of corrected movements beyond the clinical setting. It has been shown that one can manipulate the adaptation process to induce greater after-effects within the same context (Morehead et al., 2015; Marinovic et al., 2017; Finley et al., 2015; Yokoyama et al., 2018), but it remains to determine whether more after-effects in the training context would lead to more after-effects in a different environment. It has been shown that incline split-belt treadmill walking would lead to greater adaptation effects (i.e., after-effects) in both young (Sombric et al., 2019) and post-stroke patients (Sombric and Torres-Oviedo, 2020) in the training context (i.e., treadmill). However, we do not know if increasing the sensorimotor adaptation within the training context by inclining the treadmill would increase the generalization of adapted movements from split-belt treadmill to overground walking. Therefore, we will determine whether incline adaptation can manipulate the generalization of locomotor adaptation in young healthy adults.

While incline walking can improve locomotor adaptation, it decreases the contextual similarity between the incline treadmill and flat overground walking, since the forces that one needs to produce under these two conditions are different (Lay et al., 2006, 2007). Also, it has been shown that decreasing the similarity between the training and the testing environments in sensory, motor, and cognitive contextual features limit motor corrections to the training device (Ahmed et al., 2008; Ingram et al., 2010; Torres-Oviedo and Bastian, 2010; Hirashima and Nozaki, 2012). For example, the visual information during walking is quite different between the treadmill and overground environments. It has been shown that by making the visual information more similar between the training (i.e., treadmill) and the testing (i.e., overground) environments during split-belt treadmill adaptation, we can partially improve the transfer of movements (i.e., generalization) from the treadmill to overground walking (Torres-Oviedo and Bastian, 2010). On the other hand, previous studies have shown that increasing similarity between the training and testing settings improves the generalization of motor patterns from the trained to untrained contexts (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). Thus, we are interested to know if decreasing the similarity between the training and testing conditions (i.e., manipulating the ground reaction forces) while inducing more adaptation with incline walking would lead to more transfer of movements from treadmill to overground walking.

In this study, we investigated the impact of similarity and the extent of adaptation on the generalization of locomotor learning. To this end, we manipulated the training condition by increasing the extent to which participants adapt at the expense of decreasing the similarity between the training and the testing environment. We hypothesized that increasing the extent of sensorimotor recalibration would lead to greater generalization despite the differences between the training and the testing environment. To test our hypothesis, we compared the generalization of movements from the two adaptation settings (i.e., flat vs. incline) by quantifying movement after-effects when tested overground. If incline adaptation leads to greater after-effects overground, we could conclude that increasing the extent of adaptation would be beneficial for generalizing the movements beyond the training environments.

3.2 Methods

3.2.1 Participants

We investigated the effect of similarity and the extent of adaptation on the generalization of recalibrated movements to overground walking. To this end, we evaluated the kinetic and kinematic adaptation and after-effects of 16 young healthy participants (8 men and 8 women, 25.7±6.1 years of age) randomly assigned to one of 2 groups experiencing the split-belt adaptation protocol in a flat, or incline configuration (n = 8 each). All participants were neurologically intact, young adults who were naive to the experimental protocol and have never experienced split-belt walking. The Institutional Review Board at the University of Pittsburgh approved our experimental protocol and all participants gave their written informed consent before being tested.

3.2.2 Locomotor Paradigm

All participants walked both overground and on a treadmill during the experiment to complete a conventional generalization protocol that consisted of three walking epochs: baseline, adaptation, and post-adaptation (Figure 10A-top). First, participants experienced the baseline epoch overground, during which they walked back-and-forth on a 9 m walkway (i.e., overground walking) for 150 strides before walking on the treadmill. Then, participants experienced the baseline epoch on the flat or incline (8.5°) treadmill, during which they walked on the treadmill for three different speeds, which were slow (0.5 m/s), fast (1.5 m/s), and medium (1 m/s) for 150 strides each. Next, participants experienced either a flat or incline split-belt adaptation epoch for 600 strides in which the belts moved at a 3:1 belt ratio (1.5 and 0.5 m/s). The faster belt was under the dominant leg for every participant, which was determined by self-report of preferred kicking leg (Kramer and Balsor, 1990). Next, in the post-adaptation phase, participants walked overground, for 450 strides to assess the generalization of treadmill aftereffects to a different walking condition. Participants did not take any transition steps between walking on the treadmill and walking overground. Following the overground walking, participants walked again on the treadmill either flat or incline for

300 strides when the two belts moving at 1 m/s to assess the remaining aftereffects that were specific to the training context.

For safety purposes, all individuals wore a ceiling-mounted harness during the entire paradigm that only provided support in the event of a fall. For the treadmill walking conditions, participants were alerted when the treadmill was about to start and stop but they were not informed about the speed of the belts. Participants were instructed to hold on to a handrail positioned on the left side of them at the beginning and end of each treadmill condition but were encouraged to let go as soon as they felt comfortable walking with their arms unrestricted (as they did during overground walking). Participants were also instructed to look straight ahead while walking so that they would not gain visual information about the belt speeds by looking down at the belts. (An examiner stood by to monitor compliance with these instructions). Also, a plastic divider was placed between the treadmill belts to ensure that participants could not step on the wrong belt when walking on the treadmill.

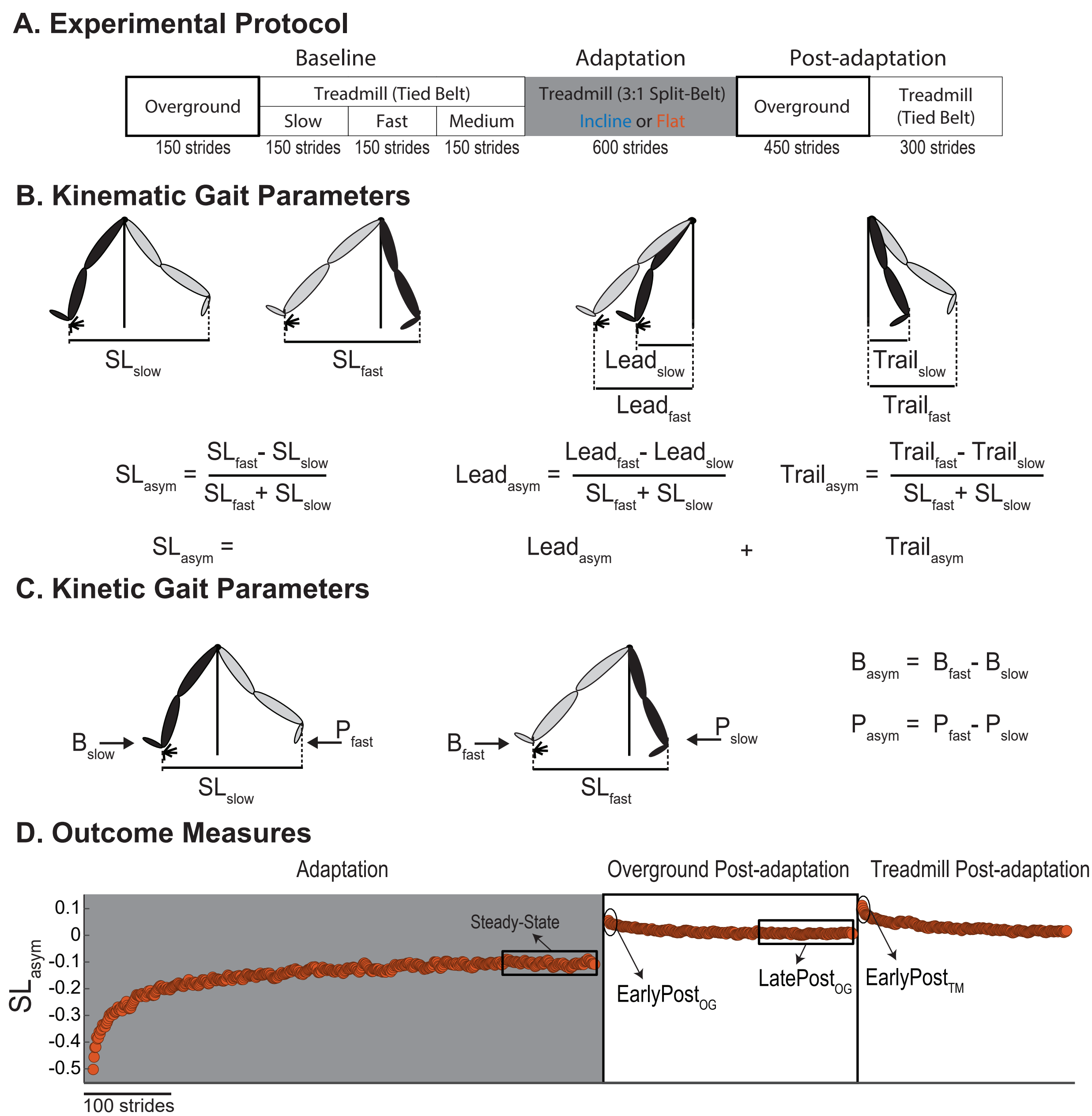


Figure 10: (A) Experimental protocol. The paradigm used for both groups consisted of 3 phases: baseline, adaptation, and post-adaptation. Thick black outlines represent overground walking. Thin black outlines represent treadmill conditions with both belts moving at the same speed (i.e., tied). The gray background represents the adaptation period that the dominant leg is moving three times faster than the non-dominant leg (i.e., split). (B) This schematic illustrates step length asymmetry and its decomposition into leading and trailing leg asymmetries (i.e., kinematic measures). Step length asymmetry is quantified as the difference between fast and slow step lengths, normalized by stride length. The equation and decomposition are explained in detail in the section "Materials and Methods" of this article. In brief, the asymmetry between the fast (gray) and the slow (black) leading leg's positions contribute to step length asymmetry. Similarly, asymmetry in

the trailing leg's positions also contributes to step length asymmetry. (C) This schematic illustrates kinetic measures. The peak braking force was quantified as the minimum value of the anterior-posterior force for the slow and fast leg (i.e., B_{slow} and B_{fast}, respectively), whereas the peak propulsion force was quantified as the maximum value of the anterior-posterior force for the slow and fast leg (P_{slow} and P_{fast}, respectively). The equation and decomposition are explained in detail in the section "Materials and Methods" of this article. The asymmetry between the fast (gray) and the slow (black) braking and propulsion forces is quantified as the difference between the fast and the slow side. (D) Outcome measures. Epochs of interest are illustrated over an example step length asymmetry time course. The shaded gray area represents the adaptation period when the feet move at different speeds ("split" walking), whereas white areas represent when the feet move at the same speed. Think black outline represents the overground condition.

3.2.3 Data Collection

Kinematic and kinetic data were collected at 100 Hz and 1000 Hz, respectively. Kinematic data were collected using a passive motion capture system (Vicon Motion Systems, Oxford UK), whereas an instrumented split-belt treadmill (Bertec, Columbus OH), and 4 overground force-plates (Bertec, Columbus OH) were used to collect the kinetic data. Positions from the ankle (lateral malleolus) and the hip (greater trochanter) were collected bilaterally. Markers were also placed asymmetrically on the shanks and thighs to differentiate between the legs. Gaps in raw kinematic data due to marker occlusion were filled by visual inspection of each participant in Vicon Nexus software. Ground reaction forces recorded by force plates under each treadmill belt were used to count in real-time the number of strides that participants walked on the treadmill. We used the ankle markers (i.e., the maximum difference between the two markers in the anterior-posterior direction) to count steps for the overground trials since we did not have force-plates available along the entire overground walking path. Following data collection, instances of heel-strikes (i.e. foot landing) and toe-offs (i.e., foot lifting) were identified using kinematic data. This was done to have equivalent event detection on the treadmill and overground as in previous generalization studies (Sombric et al., 2017; Mariscal et al., 2020; Torres-Oviedo and Bastian, 2010, 2012). Custom MATLAB scripts were used to perform all data analysis.

3.2.4 Data Analysis

3.2.4.1 Kinematic Data Analysis We characterized the adaptation and generalization patterns of every group using step length asymmetry, which is a conventional metric in split-belt protocols. Step length asymmetry (SL_{asym}) was defined as the difference between step lengths (SL, the distance between ankles) when taking a step with the leg walking slow vs. the leg walking fast (Eq. 3.1). SL_{fast} is defined as the distance between ankles at fast heel strike (i.e., Fast leg is leading), while SLslow is defined as the distance between ankles at slow heel strike (i.e., Slow leg is leading). A zero value of step length asymmetry indicated that both step lengths were equal and a positive value indicated that the step length of the fast (dominant) leg was longer than the slow (non-dominant) leg. We further decomposed step length asymmetry into asymmetries between the leading ($Lead_{asym}$) or trailing ($Trail_{asym}$) positions (Figure 1B) because these have been shown to adapt (Sombric et al., 2019; Sombric and Torres-Oviedo, 2020) and generalize differently (Mariscal et al., 2020). $Lead_{asym}$ (Eq. 3.2) and $Trail_{asym}$ (Eq. 3.3) were calculated as follows:

$$SL_{asym} = \frac{SL_{fast} - SL_{slow}}{SL_{fast} + SL_{slow}} \tag{3.1}$$

$$Lead_{asym} = \frac{Lead_{fast} - Lead_{slow}}{SL_{fast} + SL_{slow}} \tag{3.2}$$

$$Trail_{asym} = \frac{Trail_{fast} - Trail_{slow}}{SL_{fast} + SL_{slow}} \tag{3.3}$$

In these equations, the leading leg's position ($Lead_{fast}$ or $Lead_{slow}$) was defined as the ankle's marker position in the sagittal plane of the leg in front of the body at heel-strike and the trailing leg's position ($Trail_{fast}$ or $Trail_{slow}$) was defined as that of the leg behind the body. Both positions are computed with respect to the body, which is defined as the averaged position of the two hip markers at heel-strike. Moreover, the leading leg's position $Lead_{fast}$

was the position of the fast leg when this was in front of the body at fast heel-strike, whereas $Lead_{slow}$ was the same but when the slow leg was the leading leg. By convention, positive ($Lead_{asym}$) values indicated that the fast leg landed farther forward from the body compared to when the slow leg landed forward when taking a step. Similarly, the trailing leg's position $Trail_{fast}$ was the position of the fast leg when this was the trailing leg at slow heel strike and vice versa for $Trail_{slow}$. By convention, negative $Trail_{asym}$ values indicated that the fast leg was farther behind the body compared to when the slow leg was behind the body at heel strike.

3.2.4.2 Kinetic Data Analysis Kinetic data were used to characterize the adaptation and generalization¬ of ground reaction forces, which are the forces generated at our feet during walking. This information would provide us with insight into the movement vigor (Marinovic et al., 2017) and stiffness of the joints (Casadio et al., 2015) in the generalization of motor patterns adapted on the treadmill. The kinetic analysis was focused on forces in the anterior-posterior direction since these are modulated by inclination (Lay et al., 2006) and they are adapted during split-belt walking (Ogawa et al., 2014; Sombric et al., 2019; Sombric and Torres-Oviedo, 2020). The anterior-posterior ground reaction forces (AP forces) were first low-pass filtered with a cutoff frequency of 20 Hz. Then, they were normalized by each participants' body weight to account for inter-subject differences. The force data were divided into intervals of the gait cycle and aligned to heel strike events to focus on changes in ground reaction forces within the gait cycle, rather than on changes due to differences in the timing of the gait cycle across the distinct walking conditions Dietz et al. (1994); Reisman et al. (2005). The AP forces were further decomposed into peak braking and peak propulsion forces for each stride. The peak braking force was quantified as the minimum value of the AP force for the slow and fast leg (Figure 10C; B_{slow} and B_{fast}, respectively), whereas the peak propulsion force was quantified as the maximum value of the AP force for the slow and fast leg (Figure 10C; P_{slow} and P_{fast}, respectively). We systematically excluded maxima values occurring before the braking force. Thus, we did not consider the initial positive AP forces following heel strike in the identification of propulsion forces. Since we wanted to contrast between the kinematic and kinetic measures in adaptation and generalization of movements, we looked at the asymmetry measures in braking (B_{asym}) and propulsion P_{asym} forces to make them as comparable as possible. B_{asym} (Eq. 3.4) and P_{asym} (Eq. 3.5) were calculated as follows:

$$B_{asym} = B_{fast} - B_{slow} \tag{3.4}$$

$$P_{asym} = P_{fast} - P_{slow} \tag{3.5}$$

Peak forces were used to characterize braking and propulsion to be consistent with prior split-belt studies (Mawase et al., 2013; Ogawa et al., 2014; Sombric et al., 2019; Sombric and Torres-Oviedo, 2020) and those reporting kinetic differences between inclinations (Lay et al., 2006; Item-Glatthorn et al., 2016). Note that we did not remove slope-specific biases due to gravity because we focused on analyzing changes in braking and propulsion forces between epochs of interest.

3.2.5 Outcome Measures

Outcome measures were computed for each gait parameter at specific epochs of interest within the experimental protocol. These outcome measures consisted of 1) steady-state, 2) change in adaptation 3) early aftereffects overground, 4) late aftereffects overground, and 5) remaining aftereffects on the treadmill. These outcome measures were used to compare the adaptation and generalization between the groups (Figure 10C). In all outcome measures, we first removed the five strides at the end of each epoch to eliminate the effect of slowing down before stopping.

It has been shown that incline and flat split-belt adaptation would lead to different adaptation states in both healthy (Sombric et al., 2019) and post-stroke patients (Sombric and Torres-Oviedo, 2020). Therefore, we quantified the steady-state (SteadyState, average of last 40 strides) to contrast the adapted states between groups before testing participants overground. Next, we characterized the changes from early to late adaptation (ΔAdapt, average of last 40 strides – average of first 10 strides) to quantify the extent of adaptation in each of the groups. Positive values mean that there is an increase in the magnitude of a parameter within an epoch and vice versa. Then, we quantified early aftereffects overground (EarlyPost$_{\mathrm{OG}}$, averaged of first 10 strides) during the initial steps of the post-adaptation epoch to assess the generalization of movements from the treadmill (i.e., training environment) to the overground walking environment (i.e., testing). The purpose of analyzing the late aftereffects overground (LatePost$_{\mathrm{OG}}$, average of last 40 strides) was to verify whether the participants went back to their baseline values before assessing the remaining aftereffects on the treadmill. Lastly, we looked at the remaining aftereffects on the treadmill (i.e., EarlyPost$_{\mathrm{TM}}$) to assess the size of aftereffects that was not washed out during overground post-adaptation walking. We removed participant-specific biases on the treadmill or overground before aggregating the participants for group analyses. In other words, we subtracted the Baseline bias of each participant that matched the epoch of interest in terms of the environment (i.e., treadmill vs. overground).

In addition, we quantified the magnitude of aftereffects as a percentage of ΔAdapt as shown below, this was done to evaluate the generalization and washout during overground post-adaptation as a percentage of adaptation:

$$\%Gen = \frac{EarlyPost_{OG}}{\Delta Adapt} \tag{3.6}$$

$$\%Washout = 100 - \frac{EarlyPost_{TM}}{\Delta Adapt} \tag{3.7}$$

In these equations, EarlyPost$_{\mathrm{OG}}$ and EarlyPost$_{\mathrm{TM}}$ refer to the unbiased values during early overground and treadmill post-adaptation, respectively. The %Gen and %Washout metrics were computed only if the parameter of interest had a Adapt which was significantly different from zero to avoid numerically unstable values, resulting in unrealistic values of %Gen and % Washout. A value of 100% of %Gen would indicate that there is full carry-over of updated movements from the treadmill to overground walking, whereas a value of 0% would indicate no transfer of movements across conditions. On the other hand, a value of 100% for %Washout would indicate that there is no remaining aftereffect on the treadmill, whereas a value of 0% would indicate that there is a full remaining aftereffect in the training environment.

3.2.6 Statistical Analysis

We performed one-sample Kolmogorov–Smirnov tests to determine if each parameter (i.e. Step length asymmetry, $Lead_{asym}$, $Trail_{asym}$) was normally distributed in every epoch of interest (i.e., LAdapt, $EarlyPost_{OG}$, $LatePost_{OG}$, $EarlyPost_{TM}$, and ΔAdapt). We found that all parameters were normally distributed, thus we ran separate unpaired t-tests to determine the effects of training (i.e., Flat vs. Incline) on generalization in each of our gait parameters. Statistical analysis was done with unbiased data (i.e. condition-specific baseline was subtracted from all the epochs) to focus on changes that occurred beyond those due to distinct group biases. We corrected for multiple comparisons using a Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995) that we have used before (Aucie et al., 2020), in which we corrected the significance threshold for each epoch by setting a false discovery rate of 5% (FDR correction). Consequently, a p-value < 0.021 and 0.0099 was significant considering the FDR correction for comparing between groups and comparing to zero, respectively. Lastly, we performed a one-sided one-sample t-test to determine whether Adapt, $EarlyPost_{OG}$, $LatePost_{OG}$, and $EarlyPost_{TM}$, and values were different from zero. Specifically, ΔAdapt provided us information on whether each group was significantly adapted. We also wanted to determine if each group had significant overground aftereffects ($EarlyPost_{OG}$) and remaining treadmill aftereffects ($EarlyPost_{TM}$). Lastly, we used $LatePost_{OG}$ to make sure that both groups went back to baseline behavior by the end of overground post-adaptation before returning to the treadmill. MATLAB (TheMathWorks, Inc., Natick, MA, United States) was used to perform all the analyses.

3.2.6.1 Power Analysis

We hypothesized that increasing the extent of sensorimotor recalibration would lead to greater generalization despite the differences between the training and the testing environment. To test this hypothesis, we contrasted the differences between the aftereffects when participants were adapted incline or flat. Therefore, we performed a power analysis to ensure that the study would be adequately powered to detect a meaningful difference between the aftereffects. The number of participants per group was determined using the aftereffects for the incline and flat groups from Sombric et al. (2019) and scaling it by 40% to account for smaller overground transfer based on previous literature (Torres-Oviedo and Bastian, 2012). We specifically used an unpaired t-test procedure. The mean and the standard deviation for the incline group were 0.43 and 0.14, whereas they were 0.22 and 0.062 for the flat group. This led to the effect size of 1.94 when comparing the aftereffects of the incline and the flat group. Our power analysis indicated that an estimated sample size of n = 6 participants per group would allow us to detect said effect size with a significant level of $\alpha = 0.05$ and statistical power of 80% (i.e., $\beta = 0.8$). However, we chose 8 subjects to be consistent with previous literature generalization protocols (Sombric et al., 2017). All statistical analyses were done using G*Power. We chose this power to ensure that any insignificant difference between the groups was not due to a lack of power in our sample size.

3.3 Results

3.3.1 Incline Split-belt Walking Led to more Adaptation of Walking Patterns in Kinematic but not Kinetic Measures

In general, we observed that participants in the incline group had larger changes during the adaptation period in the kinematic measures. We found that both groups exhibited changes in adaptation (i.e., Δadapt) that were significantly different from zero in all parameters, except P_{asym} (Table 4). This means that on average ΔAdapt is different from zero in all parameters except for P_{asym}, which might be due to the inter-subject variability.

Moreover, participants adjusted their movement more when adapted incline compared to when adapted flat. Figures 11A, B, and C indicate the time courses for SL_{asym}, $Lead_{asym}$, and $Trial_{asym}$ during adaptation. Note that participants who adapted incline (i.e., blue dots) had a larger change from early to late adaptation compared to those who adapted flat (i.e., orange dots). Accordingly, we observed that the changes from early to late adaptation are different between groups in SL_{asym} ($p = 0.0055$, $t = 3.28$, $d = 1.64$), $Lead_{asym}$ ($p = 0.0024$, $t = 3.69$, $d = 1.85$), $Trail_{asym}$ ($p = 0.021$, $t = 2.59$, $d = 1.29$) (Figures 11D, E, F). Figures 12A and B indicate the time courses for B_{asym}, and P_{asym} during adaptation. In contrast to our kinematic measures, we found that the participants in the incline group adjusted their movement less than the flat group in the B_{asym} ($p = 0.0059$, $t = 3.24$, $d = 1.62$) (Figure 12C) and group differences were not significant in P_{asym} ($p = 0.12$, $t = -1.67$, $d = -0.83$) (Figure 12D). The lack of group difference in P_{asym} might also be due to large inter-subject variability. In summary, incline adaptation led to larger kinematic, but smaller kinetic changes during adaptation in split-belt walking.

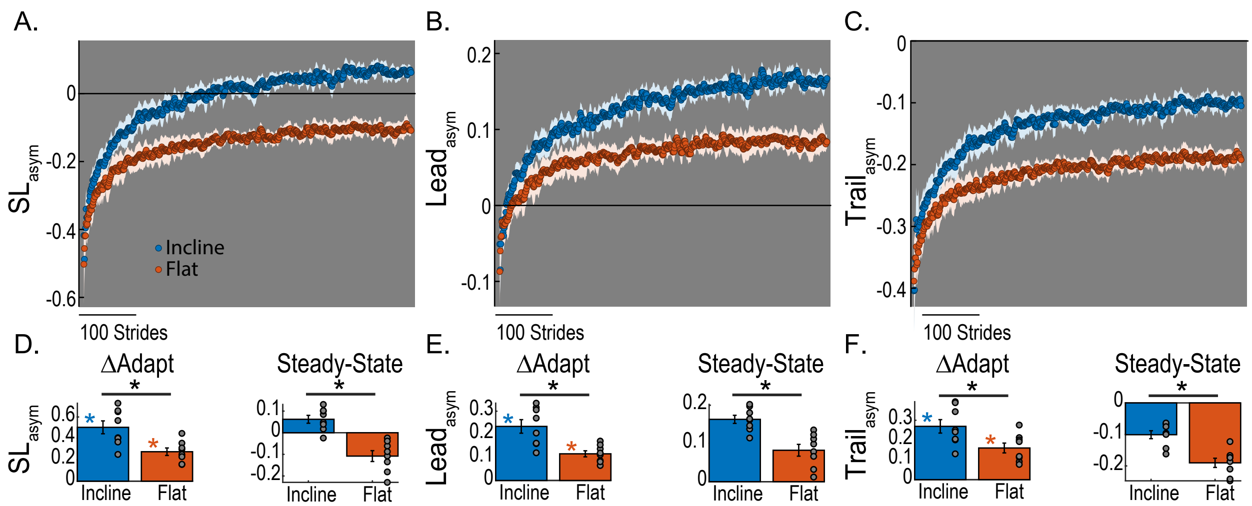


Figure 11: Adaptation of step length asymmetry and its decomposition. (A-B-C) Time courses for step length asymmetry, lead, and trail asymmetry during the adaptation period for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (D-E-F) Bar plots indicate the mean and standard errors for each group for the ΔAdapt and steady-states. Colored asterisks denote group averages significantly different from zero. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased (i.e., bias in each participant during baseline on the treadmill was subtracted before calculating outcome measures).

Furthermore, we observed that participants in the incline group reached higher steady-state values during the adaptation in kinematic measures while reaching lower steady-states in the kinetic measures. Specifically, the statistical analysis revealed that the incline group reached significantly higher steady-states on all kinematic (SL_{asym}: $p < 0.0001$, $t = 5.49$, $d = 2.75$; $Lead_{asym}$: $p < 0.0001$, $t = 4.32$, $d = 2.16$; $Trail_{asym}$: $p < 0.0001$, $t = 4.63$, $d = 2.31$) (Figures 11D, E, and F), but lower steady-states on all kinetic (B_{asym}: $p = 0.0103$, $t = -2.96$, $d = -1.48$; P_{asym}: $p < 0.0001$, $t = -4.79$, $d = -2.39$) measures at the end of adaptation (Figures 12C, D). To sum up, the incline walking led to higher steady-state values of kinematic, but lower steady-state of kinetic measures during adaptation.

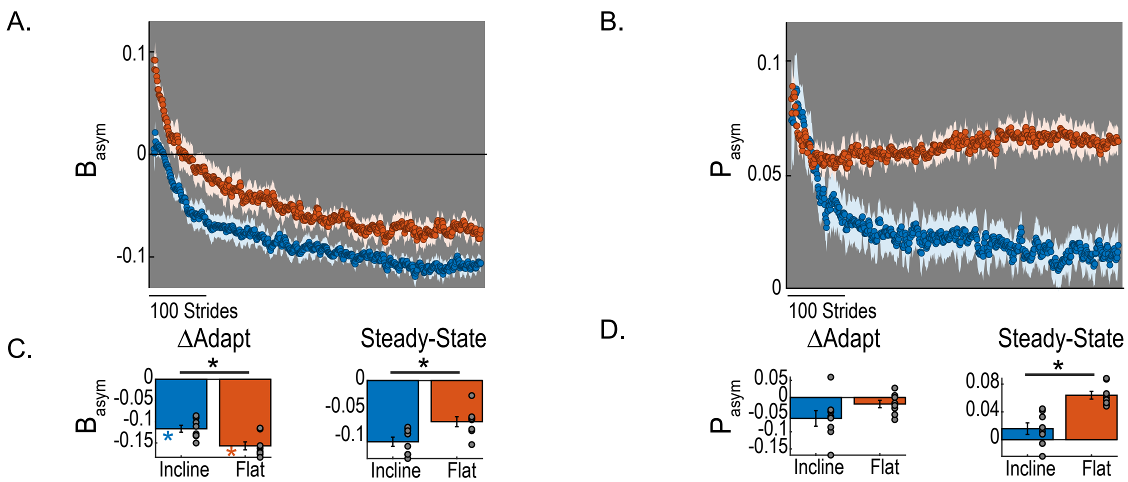


Figure 12: Adaptation of braking and propulsion asymmetry. (A-B) Time courses for brake, and propulsion asymmetry during the adaptation period for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (C-D) Bar plots indicate the mean and standard errors for each group for the ΔAdapt and steady-states. Colored asterisks denote group averages significantly different from zero. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased (i.e., bias in each participant during baseline on the treadmill was subtracted before calculating outcome measures).

Table 4: Changes during adaptation on the treadmill (ΔAdapt)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Incline	< 0.0001	8.36	2.96
Flat	< 0.0001	7.88	2.79
$Lead_{asym}$:			
Incline	< 0.0001	7.99	2.83
Flat	< 0.0001	8.79	3.11
$Trail_{asym}$:			
Incline	< 0.0001	7.93	2.80
Flat	< 0.0001	6.43	2.27
B_{asym}:			
Incline	< 0.0001	-14.3	-5.07
Flat	< 0.0001	-16.7	-5.91
P_{asym}:			
Incline	0.032 (n.s)	-2.67	-0.94
Flat	0.12	-1.77	-0.63

3.3.2 Flat Split-belt Walking led to Greater Generalization Compared to Incline Split-belt Walking in Kinematic, but not Kinetic Measures

While incline walking resulted in more adaptation than flat, the incline group generalized less than the flat group. Both groups exhibited initial overground aftereffects that were significantly different from zero in SL_{asym}, and $Trail_{asym}$, but not in $Lead_{asym}$ (See $EarlyPost_{OG}$

results in Table 5). Figures 13A, B, and C show time courses of SL_{asym}, $Lead_{asym}$, and $Trial_{asym}$ during overground post-adaptation in both incline and flat groups. We observed that the flat group (i.e., orange dots) has larger aftereffects when walking overground than the incline group (i.e., blue dots) in SL_{asym}, and $Trail_{asym}$ but these group differences were not observed in $Lead_{asym}$. Accordingly, we found a significant difference on the initial overground aftereffects (i.e., $EarlyPost_{OG}$) for SL_{asym} ($p = 0.016$, $t = -2.74$, $d = -1.37$) and $Trail_{asym}$ ($p = 0.001$, $t = -4.12$, $d = -2.06$), but not $Lead_{asym}$ ($p = 0.82$, $t = -0.24$, $d = -0.12$) between the incline and flat groups (Figures 13D, E, and F). This inclination effect was also observed in %Gen, which quantified the initial aftereffects overground (testing context) as a percentage of the changes during adaptation on the treadmill (training context). Namely, %Gen of SL_{asym} ($p < 0.0001$, $t = -4.45$, $d = -2.23$) and $Trail_{asym}$ ($p < 0.0001$, $t = -4.48$, $d = -2.24$) were significantly larger in the flat than incline group. These differences were again not $Lead_{asym}$ ($p = 0.87$, $t = -0.082$, $d = -0.16$). The differences between the groups in the kinematic measures in overground aftereffects were not observed by the end of the post-adaptation period overground (i.e., $LatePost_{OG}$). Also, the aftereffects in $EarlyPost_{OG}$ went away by the end of overground walking during post-adaptation in all kinematic parameters (Table 6).

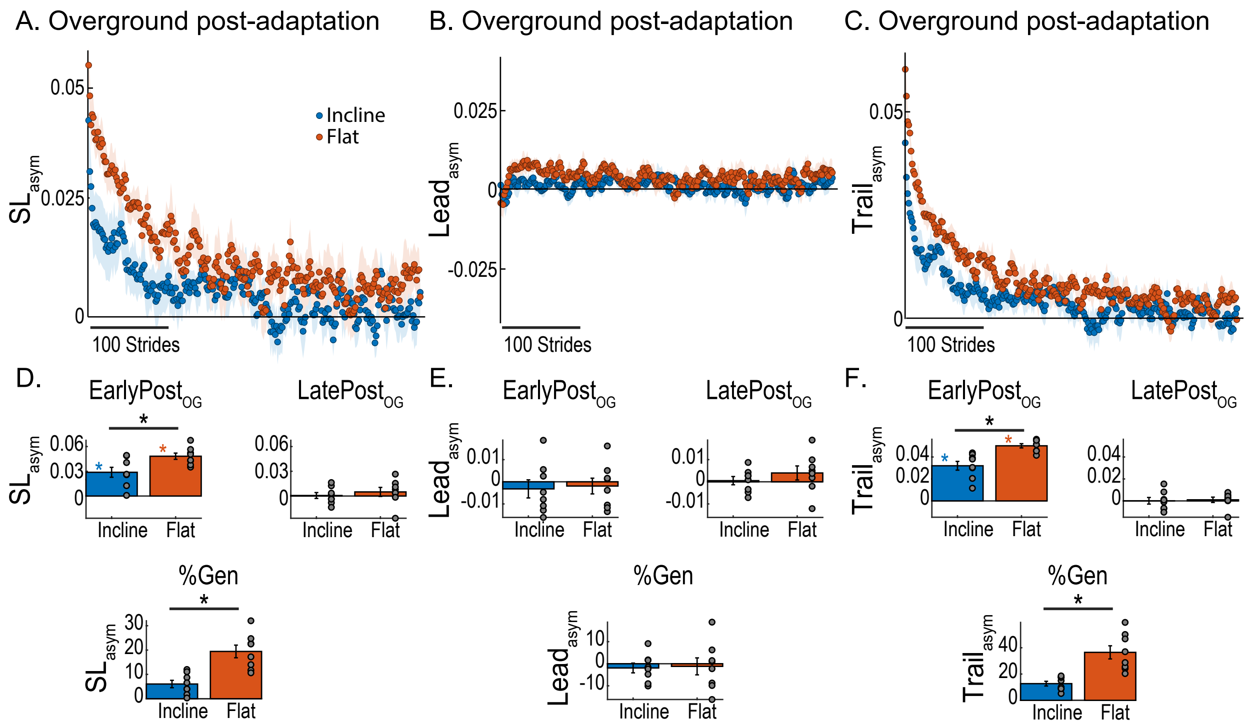


Figure 13: Generalization of step length asymmetry and its decomposition. (A-B-C) Time courses for step length, lead, and trail asymmetry during overground walking post-adaptation for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (D-top,E-top,F-top) Bar plots indicate the mean and standard errors for each group's initial (EarlyPost$_{\mathrm{OG}}$) and final (LatePost$_{\mathrm{OG}}$) aftereffects during overground post-adaptation. Colored asterisks denote group averages significantly different from zero. (D-bottom,E-bottom,F-bottom) %Generalization for each group. This measure indicates the size of initial aftereffects expressed as a percentage of the ΔAdapt. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking overground.

Table 5: Initial aftereffects during overground post-adaptation ($\text{EarlyPost}_{\text{OG}}$)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Incline	0.002	4.78	1.69
Flat	< 0.0001	12.8	4.52
$Lead_{asym}$:			
Incline	0.46	-0.79	-0.28
Flat	0.61	-0.54	-0.19
$Trail_{asym}$:			
Incline	< 0.0001	8.03	2.84
Flat	< 0.0001	26.4	9.32
B_{asym}:			
Incline	0.0038	-4.25	-1.50
Flat	0.0011	-5.29	-1.87
P_{asym}:			
Incline	0.19	-1.44	-0.51
Flat	0.23	-1.30	-0.46

Table 6: Final aftereffects during overground post-adaptation ($LatePost_{OG}$)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Incline	0.87	0.17	0.061
Flat	0.39	0.91	0.32
$Lead_{asym}$:			
Incline	0.79	0.27	0.097
Flat	0.25	1.26	0.44
$Trail_{asym}$:			
Incline	0.97	0.035	0.012
Flat	0.69	0.41	0.15
B_{asym}:			
Incline	0.08	-2.07	-0.73
Flat	0.063	-2.39	-0.84
P_{asym}:			
Incline	0.65	0.48	0.17
Flat	0.71	-0.39	-0.14

While there is more adaptation of kinetic measures in the flat condition compared to incline, we observed the same level of after-effects across groups when walking overground. Both groups exhibited initial overground aftereffects that were significantly different from zero in B_{asym}, but not in P_{asym} (See $EarlyPost_{OG}$ results in Table 2). Figures 14A, and B show time courses of B_{asym}, and P_{asym} during overground post-adaptation in both incline (i.e., blue dots) and flat (i.e., orange dots) groups. We did not observe any group differences in the kinetic measure asymmetries neither in raw values (B_{asym}: $p = 0.71$, $t = 0.37$, $d = 0.19$; P_{asym}: $p = 0.79$, $t = 0.27$, $d = 0.13$) nor in %Gen of B_{asym} ($p = 0.67$, $t = 0.44$, $d = 0.22$) (Figures 14C, and D). Consistently, we did not observe any group differences or aftereffects in B_{asym} (Table 6) at the end of overground walking during post-adaptation (i.e., $LatePost_{OG}$). Overall, we observed that flat adaptation leads to greater generalization compared to incline walking in the kinematic, but not in kinetic measures.

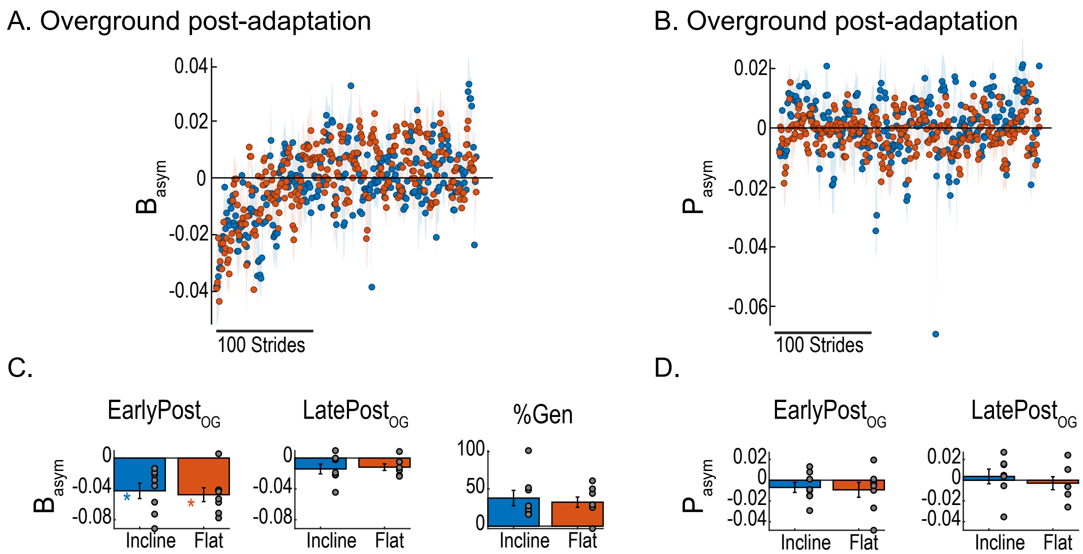


Figure 14: Generalization of braking and propulsion asymmetry. (A-B) Time courses for brake, and propulsion asymmetry during overground walking post-adaptation for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (C, D) Bar plots indicate the mean and standard errors for each group's initial ($EarlyPost_{OG}$) and final ($LatePost_{OG}$) aftereffects during overground post-adaptation. Colored asterisks denote group averages significantly different from zero. (C-right) %Generalization for each group for braking asymmetry. This measure indicates the size of initial aftereffects expressed as a percentage of the ΔAdapt. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking overground.

3.3.3 Similar Washout of Kinematic Across Groups, but Larger Washout of Kinetic Patterns in the Flat Compared to the Incline Group

We observed that inclination affected the remaining aftereffects when participants returned to the treadmill after walking overground. Figures 15A, B, and C show the time courses of the remaining aftereffects during post-adaptation on the treadmill. We observed that both groups had aftereffects that were significantly different from zero in all asymmetry parameters (see Table 7). However, the flat group (i.e., orange dots) had smaller remaining aftereffects than those who adapted incline (i.e., blue dots). Consistently, the initial aftereffects during treadmill post-adaptation ($\text{EarlyPost}_{\text{TM}}$) was significantly smaller in the Flat than in the Incline groups for all kinematic measures (SL_{asym}: $p = 0.0011$, $t = 4.09$, $d = 2.04$; $\text{Lead}_{\text{asym}}$: $p < 0.0001$, $t = 4.57$, $d = 2.28$; $\text{Trail}_{\text{asym}}$: $p = 0.0092$, $t = 3.02$, $d = 1.51$) (Figures 15D, E, and F). However, these differences were not present when the remaining aftereffects were expressed as a percent of ΔAdapt (i.e., %Washout) for any of the parameters (SL_{asym}: $p = 0.39$, $t = -0.89$, $d = -0.44$; $\text{Lead}_{\text{asym}}$: $p = 0.04$, $t = -2.27$, $d = -1.13$; $\text{Trail}_{\text{asym}}$: $p = 0.86$, $t = 0.17$, $d = 0.087$). In sum, we saw a larger remaining aftereffect in the incline group in $\text{EarlyPost}_{\text{TM}}$, but not %Washout in kinematic measures compared to the flat group.

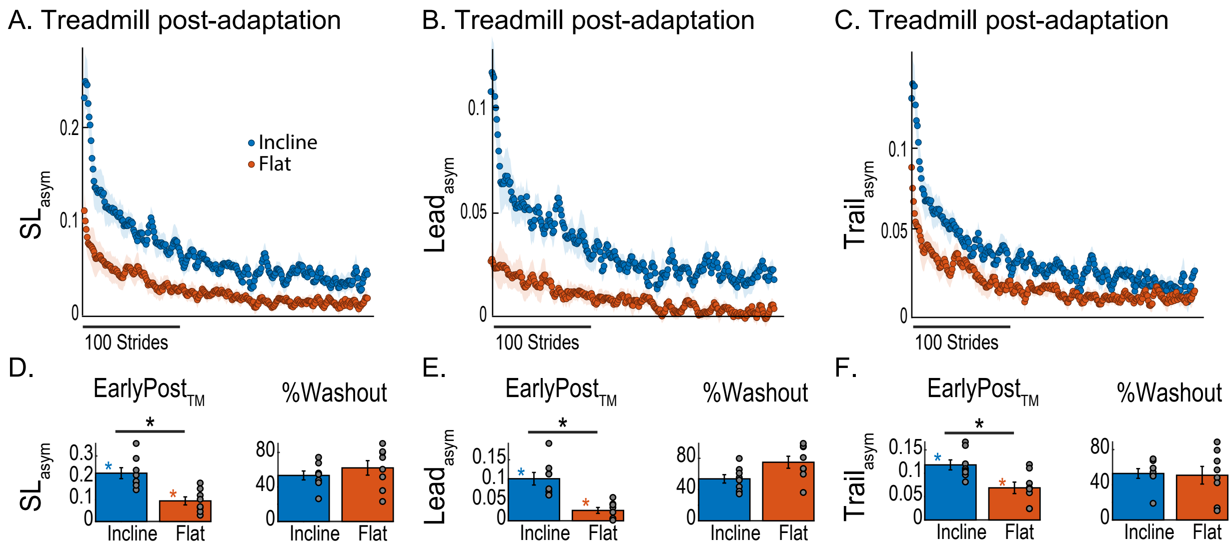


Figure 15: Aftereffects on the treadmill of all kinematic asymmetry parameters. (A-B-C) Time courses for step length, lead, and trail asymmetry when walking on the treadmill during post-adaptation for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (D-Left,E-Left,F-Left) Bar plots indicate the mean and standard errors for each group's initial aftereffects on the treadmill following overground walking. Colored asterisks denote group averages significantly different from zero. (D-Right, E-Right, F-Right) %Washout for each group for all kinematic asymmetry parameters. This measure indicates the size of initial aftereffects expressed as a percentage of the ΔAdapt. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking on the treadmill at medium speed (i.e., 1 m/s).

Table 7: Initial aftereffects during treadmill post-adaptation ($EarlyPost_{TM}$)

Outcome measure for each Group	p-value	t-value	Effect size (Cohen's d)
SL_{asym}:			
Incline	< 0.0001	8.84	3.12
Flat	0.0014	5.13	1.81
$Lead_{asym}$:			
Incline	< 0.0001	6.69	2.37
Flat	0.009	3.51	1.24
$Trail_{asym}$:			
Incline	< 0.0001	11.1	3.90
Flat	< 0.0001	5.59	1.98
B_{asym}:			
Incline	< 0.0001	-15.8	-5.60
Flat	< 0.0001	-6.94	-2.45
B_{asym}:			
Incline	< 0.0001	-9.06	-3.20
Flat	0.0058	-3.91	-1.38

While we found that both groups exhibit the same %Washout in the kinematic measures, we observed more %Washout in the kinetic measures of the flat (i.e., orange dots) group compared to the incline (i.e., blue dots) group. Figures 16A and B show the averaged aftereffects for both groups on the treadmill during post-adaptation walking for the B_{asym} and P_{asym}. We observed significant treadmill aftereffects for both kinetic parameters in both groups (Table 7). Furthermore, we observed a larger remaining aftereffect in the incline group compared to the flat group during the treadmill post-adaptation (i.e., $EarlyPost_{TM}$) for P_{asym} ($p < 0.0001$, t = -6.52, d = -3.26), but these group differences were not observed in B_{asym} (p = 0.39, t = -0.90, d = -0.45) (Figure 16C-Left, and D). In contrast, we observed that B_{asym} (p = 0.0062, t = -3.22, d = -1.61) was different between the groups when we assessed the remaining aftereffects as a percent of ΔAdapt (i.e., %Washout) (Figure 16C-Right). Overall, overground walking washed out more the treadmill aftereffects when participants were adapted flat than when they were adapted incline.

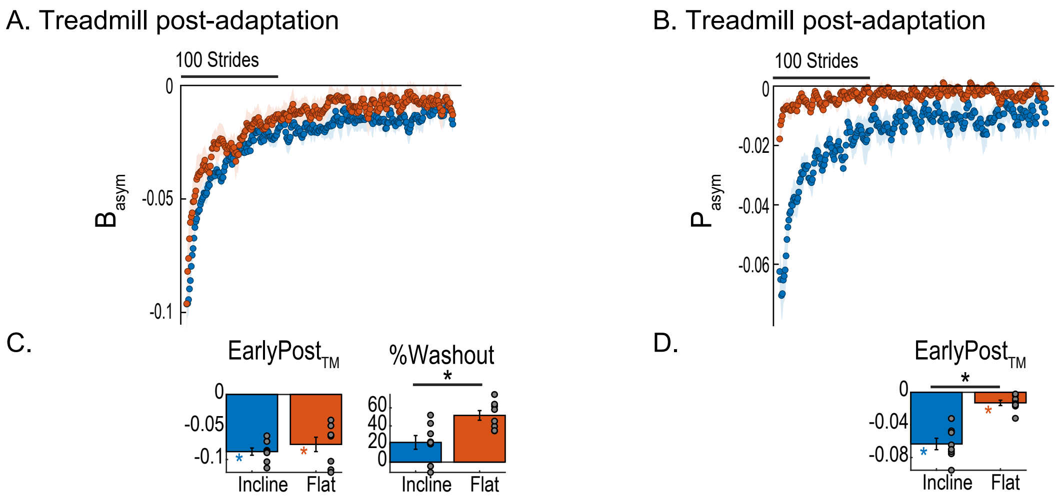


Figure 16: Aftereffects on the treadmill of all kinetic asymmetry parameters. (A-B) Time courses for brake, and propulsion asymmetry when walking on the treadmill during post-adaptation for both groups. Colored dots represent the group average of five consecutive strides and colored shaded regions indicate the standard error for each group. (C-Left, D) Bar plots indicate the mean and standard errors for each group's initial aftereffects on the treadmill following overground walking. Colored asterisks denote group averages significantly different from zero. (C-Right) %Washout for each group for all kinematic asymmetry parameters. This measure indicates the size of initial aftereffects expressed as a percentage of the ΔAdapt. In all panels, gray dots indicate values for individual participants. Note that the reported values are unbiased. This was done by subtracting the bias in each participant during baseline walking on the treadmill at medium speed (i.e., 1 m/s).

3.4 Discussion

We investigated the impact of the extent of adaptation and contextual similarity on the generalization of movements from the training to the testing environment. As we anticipated, the extent of adaptation was increased in incline compared to flat split-belt walking in kinematic measures. Surprisingly, the opposite was observed in the kinetic measures, meaning that flat adaptation led to a greater extent of adaptation compared to the incline adaptation. We know that context of flat treadmill walking is more similar to flat overground walking compared to incline treadmill walking. We found that more contextual similarity (i.e., flat adaptation) between the training (i.e., treadmill) and the testing (i.e., overground) environments led to more generalization of movements in the kinematic measures compared to a less similar context (i.e., incline adaptation). However, the effect of contextual similarity was not observed in the generalization of movements in the kinetic measures. We observed the same washout of the kinematic measures regardless of the contextual similarity. On the other hand, the more contextual similarity (i.e., flat group) between the training and the testing environments led to more washout of the kinetic measures. Taken together, the extent of adaptation and contextual similarity have a distinct impact on the adaptation and generalization of kinetic and kinematic measures suggesting that these domains can be controlled separately.

3.4.1 Incline Split-belt Walking Led to more Adaptation of Walking Patterns in Kinematic but not Kinetic Measures

Participants in the incline group had greater changes from early to late adaptation (i.e., ΔAdapt) compared to the flat group in the kinematic, but not kinetic measures. As expected, we observed more adaptation of the kinematic measures in the incline group compared to the flat group, which has been reported before in young adults (Sombric et al., 2019) and post-stroke patients (Sombric and Torres-Oviedo, 2020). We also found adaptation of the kinetic measures similar to previous studies (Ogawa et al., 2014). Surprisingly, we found that the participants in the incline group corrected their movement less than the flat group in braking asymmetry, while there was no difference between the propulsion forces. These differences in the braking asymmetry were also present in the braking force of the individual legs (i.e., fast and slow legs). Specifically, we observed more braking forces for the slow side in the flat walking compared to the incline walking. This was consistent with the previous literature that reported less braking forces in the incline walking compared to flat walking (Lay et al., 2006). Furthermore, we observed a larger reduction of the braking forces for the fast side during adaptation in the flat group compared to the incline group; however, both groups increased their fast braking forces as they adapted. Therefore, we believe that more adaptation of the braking forces in the flat group compared to the incline group is occurring for two reasons. First, participants in the flat group were perturbed more in the braking force at the beginning of adaptation (i.e., augmentation of slow braking and reduction of fast braking). Second, participants in the incline group were braking significantly less since it is not favorable to slow down while walking uphill. In other words, it is not energetically optimal to have high braking forces when walking uphill and it has been shown that the metabolic cost of walking goes down (Finley et al., 2013) during adaptation. These differences between the braking forces were not observed in the previous paper from our lab (Sombric et al., 2019) perhaps because the groups experienced a short-split perturbation before the adaptation period that affected the early behavior during adaptation and subsequently the changes throughout the adaptation. In Summary, our finding showed that the kinematic and kinetic measures adapt differently. This confirms that the movements and forces are likely to have separate neural representation as shown previously (Sergio and Kalaska, 1998; Sergio et al., 2005); even though, they need to be controlled concurrently in tasks involving mechanical interaction with the external environment.

3.4.2 The more Contextual Similarity Between the Training and Testing Environments Led to a Greater Generalization of Kinematic, but not Kinetic Measures

We found that more contextual similarity between the training and the testing environments led to larger generalizations in the kinematic measures. This was shown by our results that participants in the flat group (i.e., more similar to the testing condition) generalized more compared to the incline group (i.e., more different to the testing condition). We know from previous literature that incline walking has different contextual features (i.e., braking and propulsion forces) compared to flat walking (Lay et al., 2006, 2007). We also know that decreasing contextual similarity would lead to poor generalization (Ahmed et al., 2008; Ingram et al., 2010; Torres-Oviedo and Bastian, 2010; Hirashima and Nozaki, 2012) while increasing contextual similarity enhances generalization (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). This means that our data is consistent with previous literature showing larger generalization in the flat (i.e., more similar to the testing environment) group compared to the incline (i.e., less similar to the testing environment) group in the kinematic measures. Taken together, we revealed that contextual similarity is more important than the extent of adaptation in the generalization of movements in locomotor adaptation.

While contextual similarity impacted the generalization of the kinematic measures, we did not observe this effect in the kinetic measures. Based on previous data from our laboratory (Sombric et al., 2019) we expected to see a larger generalization in the flat group compared to the incline group. However, we observed the same generalization of the kinetic measures during overground post-adaptation. This finding is surprising for two reasons: First, the flat group adapted more in the braking forces compared to the incline group; therefore, it is expected that the flat group has more aftereffects (more negative values) than the incline group, as reported previously (Sombric et al., 2019). Second, flat adaptation has a higher contextual similarity to overground walking compared to the incline adaptation meaning that we expect a larger generalization (more aftereffect in the flat group than the incline group) in the kinetic domain (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). The investigation of the individual leg braking forces revealed that the equal generalization of the B_{asym} between the groups is due to the increased braking forces of the slow side. We know that the leg that was on the slow belt feels faster than what is expected during post-adaptation (Sombric et al., 2019). This means that the center of mass will be more forward than what is expected (i.e., the Center of mass moves faster compared to what is expected). In other words, the balance is disrupted following the adaptation (Buurke et al.,

2018) and the center of mass is moving faster than what is expected. Therefore, participants need to generate more braking forces to slow down their center of mass (Winter, 1987). Our data revealed that the flat group was more perturbed (i.e., larger step length asymmetry values) compared to the incline group in early overground post-adaptation. This means that the participants in the flat group had to generate larger braking forces compared to the incline group to slow down their center of mass. This resulted in a smaller generalization of braking forces than what was expected, which led to the equal generalization of braking forces between the groups.

Another explanation for not detecting differences in the kinetic domain might be that we had limited data in the kinetic measures compared to the kinematic during the overground data collections (our entire walkway does not have force-plates), meaning that we could not capture the same resolution as our kinematic data in the kinetic domain. Our findings of the generalization of the kinematic and kinetic measures are at odds with previous literature showing that more adaptation would lead to more generalization in visuomotor tasks (Hewitson et al., 2020). This is because the assessment of the generalization happened in the same context in the visuomotor task (i.e., training in one direction but testing in multiple directions within the same environment) while we assessed generalization of similar movement (i.e., walking) from one environment (i.e., treadmill) to another environment (i.e., overground). In summary, our results suggest that the generalization of kinetic measures is not impacted by either the contextual similarity or the extent of adaptation in locomotor adaptation.

3.4.3 Similar Washout of Kinematic Across Groups, but Larger Washout of Kinetic Patterns in the Flat Compared to the Incline Group

We observed similar washout of the kinematic measures across groups, but more washout of the kinetic measures in the flat group compared to the incline group. As expected, we observed more remaining aftereffects (i.e., raw values) in the incline group compared to the flat group in the kinematic measures. This has been reported before that incline adaptation led to more aftereffects within the same training context in both healthy adults (Sombric et al., 2019) and post-stroke patients (Sombric and Torres-Oviedo, 2020). However, when we normalized the remaining aftereffect by the extent of adaptation (i.e., %washout), we observed that the differences between the groups vanished in the kinematic measures express. This phenomenon has been observed before in split-belt adaptation paradigms that when there are different generalization levels for various reasons (i.e., age, error size, attention) the washout level is the same in the kinematic measures (Torres-Oviedo and Bastian, 2012; Sombric et al., 2017; Alcântara et al., 2018; Mariscal et al., 2020). This means that people have separate motor memories for different contexts (i.e., treadmill vs. overground) which has been reported before (Wolpert and Kawato, 1998; Heald et al., 2020). Importantly, the motor memory in one context can not be washout out in another environment even though the tasks are similar and there is generalization across environments (Cai et al., 2016). In other words, expressing larger generalization from the training environment to the testing context does not guarantee more washout of motor memory in the training environment. While there was a similar washout of the kinematic measures, we observed more washout in the flat group compared to the incline group in the kinetic domain. One explanation might be that since the experienced forces during overground are more similar to the flat treadmill walking compared to the incline walking (Lay et al., 2006), they are more susceptible to washout in that domain. In other words, the flat group experienced higher motor memory interference (Heald et al., 2020) compared to the incline group since it has higher contextual similarity between the training (i.e., Treadmill) and the testing (i.e., Overground) environments. Another explanation can be that the flat group had a higher generalization of kinetic measures to overground walking compared to the incline group and we could not detect them due to inter-subject variability and data resolution during overground walking. Also, since the kinematic and kinetic domains are likely to have separate neural representations as shown previously (Sergio and Kalaska, 1998; Sergio et al., 2005), it can lead to different adaptation, generalization, and washout of these measures. Taken together, our results suggest that the washout of kinematic and kinetic measures are independent of the generalization.

3.4.4 Study Implications

It has been suggested that split-belt protocols, such as the one presented here, can induce gait improvements in stroke survivors (Reisman et al., 2007; Savin et al., 2014; Betschart et al., 2018) that persist with repeated exposure (Reisman et al., 2013; Lewek et al., 2018). However, these improvements are mostly seen in the clinical setting and it is poorly carried over to "real-life" situations (Reisman et al., 2009) in kinematic measures. In this manuscript, we provide insight for both kinematic and kinetic measures during the overground post-adaptation that no one has reported before. Specifically, we observed that there are overground aftereffects in the braking forces, but not in the propulsion forces. This means that if a split-belt is used for gait therapy it has the potential to change the braking forces but not the propulsion forces beyond the clinical settings. This is relevant because patients with hemiparesis often exhibit deficits in their propulsion forces deficits (Bowden et al., 2006; Balasubramanian et al., 2007). In summary, our results provided important information for targeting deficits in patients with hemiparetic gait.

In addition, we observed that the generalization of movements from the training to the testing environment is more impacted by the similarity between the environments than the extent to which participants recalibrate their movement during adaptation. This is relevant not just for gait rehabilitation but also for rehabilitation of other types of movements and pieces of training. For example, previous studies have seen improvement in speech therapies (Plaut and Velde, 2017) and reaching training (Taylor and Ivry, 2013) when the training context is more similar to the testing environments. This means that our finding is valuable to any training such as performance athletes and we can benefit from devices that improve the similarity between the training and the testing environments (Aucie et al., 2020). In summary, our results revealed that the outcome of training can enhance if we maximize the similarity between the training and the testing environments contexts.

4.0 Specific Aim 3 Motorized Shoes Induce Robust Sensorimotor Adaptation in Walking

This work was published in March 2020 in Frontiers in Neuroscience (Aucie et al., 2020).

4.1 Introduction

The motor system has the flexibility to update motor plans according to systematic changes in the environment or the body. This human ability is studied in the laboratory through sensorimotor adaptation paradigms imposing sustained and predictable motor demands specific to the task at hand, such as unusual visuomotor rotations (e.g. Krakauer et al. (2000)) or constant forces during walking (Savin et al., 2010) or reaching (Shadmehr and Mussa-ivaldi, 1994) For example, split-belt walking is a well-established paradigm in which participants update spatiotemporal gait features in response to a persistent speed difference between their legs (Dietz et al., 1994; Reisman et al., 2005; Malone et al., 2012). Important motor adaptation principles have been learned from these sensorimotor adaptation paradigms, such as the computations underlying motor adaptation (Thoroughman and Shadmehr, 2000; Haruno et al., 2001; Smith et al., 2006) or neural structures involved in this process (Deuschl et al., 1996; Smith and Shadmehr, 2005; Morton and Bastian, 2006). However, there are inherent limitations to laboratory-based studies that bring into question the extent to which principles governing motor adaptation apply to motor learning in the real-world.

Specifically, there are task-constraints in laboratory-based studies that limit our ability to investigate factors that are critical for motor learning outside the laboratory setting. For example, laboratory-based protocols challenge the study of extended practice, which is a critical aspect of motor learning (Ericsson and Pool, 2016; Haith and Krakauer, 2018). There are several efforts to investigate the effect of extended practice on motor behavior by bringing participants to the laboratory multiple times (Day et al., 2018; Leech et al., 2018; Hardwick et al., 2019). This research effort would be facilitated if individuals could practice outside the laboratory setting. Further, we constrain movements by for example making people walk at a constant speed (Dietz et al., 1994), or repeatedly reach to a certain direction (Krakauer et al., 2000). This is done to simplify the control variables affecting the studied behavior, and at the extreme, this could yield to the study of unnatural behaviors, whose underlying mechanisms might not apply to realistic situations. A byproduct from task-constraints is the context-specificity of motor patterns learned in the laboratory that is movements adapted with the device only partially carry over to movements without the training device (Kluzik et al., 2008; Torres-Oviedo and Bastian, 2010). This is detrimental not only because it limits our capacity for studying the generalization of motor learning across distinct situations, but also because it limits the possibility for using laboratory-based tasks for motor rehabilitation. Notably, it is well-accepted that the generalization of motor patterns from trained to untrained situations can be improved when the two contexts are more similar to one another (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). Thus, there could be more generalization of laboratory-based knowledge to realistic situations when the tasks studied in the laboratory are more similar to those observed under naturalistic conditions.

Portable devices may offer the possibility to overcome the limitations of laboratory-based studies of motor learning. For example, portable devices allow us to investigate motor learning in real-life settings, such as studies of surgical training with the same tools that are used at the clinic (Sharon et al., 2017). In addition, the portability of training devices also enables the study of extended practice since individuals are not constrained to only train in the laboratory setting (Hardwick et al., 2019). Further, portable devices might allow for more complex movements that involve the whole body (Haar et al., 2019), which might lead to greater motor variability – a key factor for motor learning (Kelly and Sober, 2014; Wu et al., 2014; Therrien et al., 2016). In the context of locomotion there have been efforts to develop portable devices to study motor adaptation (Handzic et al., 2011; Handzic and Reed, 2013; Lahiff et al., 2016). However, the previous devices were passive, lacking the control over the speed difference between the feet. In addition, gait adjustments induced by these devices are not as robust as the ones observed with laboratory-based apparatus such as split-belt treadmills. Thus, we asked if a pair of motorized shoes could induce locomotor adaptation comparable to split-belt walking, which is a well-established sensorimotor adaptation paradigm in locomotion.

We specifically hypothesized that introducing a speed difference between participant's feet with the motorized shoes would result in adaptation of spatiotemporal gait patterns similar to split-belt walking. To test this hypothesis, we compared locomotor adaptation at comparable speed differences imposed by either a pair of motorized shoes or a split-belt treadmill. If the locomotor adaptation with the motorized shoes is similar to the one observed during split-belt walking paradigm, participants could start wearing these shoes outside the laboratory, which would offer the exciting possibility to study locomotor learning under more realistic situations.

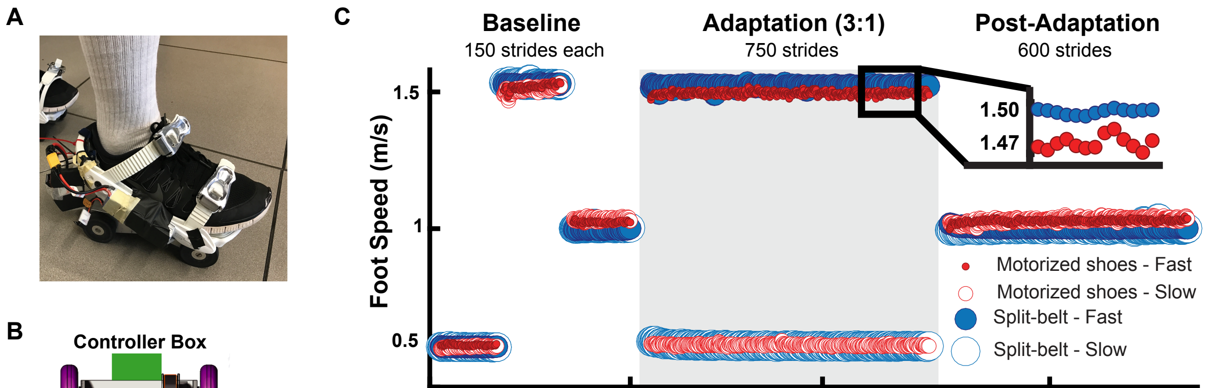
4.2 Methods

4.2.1 Participants

We investigated if a pair of motorized shoes could induce locomotor adaptation and after-effects similar to a split-belt treadmill. To this end, a group of 18 young, healthy, and naïve adults were adapted using either (1) the motorized shoes that imposed speed differences between the feet using actuated wheels under the shoe (motorized shoes group: n = 9; three females: 26.6 ± 3.5 years) or (2) a split-belt treadmill, in which belts moved at different speeds (split-belt group: n = 9; four females: 25.3 ± 4.3 years). The Institutional Review Board at the University of Pittsburgh approved our experimental protocol and all participants gave their written informed consent before being tested.

4.2.2 Set up

The motorized shoes group walked on the treadmill while wearing the custom made motorized shoes (Nimbus Robotics, Pittsburgh, PA, United States) as shown in Figure 17A on top of their normal walking shoes. In brief, the shoes were designed to move an individual (weighing $<$100 kg) up to 1 m/s in the forward direction only (i.e. wheels cannot be actuated to rotate backward). Each of the motorized shoe ($<$1.7 kg) consisted of a motor, a controller box, a gearbox, two toothed timing belts, and four rubber wheels (Figure 17B). Lithium batteries (3V) were used to power the motor, which rotated the timing belts via a gearbox connecting the two. The feet moved at different speeds with the motorized shoes by locking the wheels of one foot and actuating the wheels of the other foot, such that the combined effect of the treadmill's belt moving the foot backward and the motorized shoe moving the foot forward would result in the desired foot speed of 0.5 m/s (Figure 17B). To this end, the timing belts and rubber wheels were coupled to rotate the wheels such that they locked the non-actuated shoe during stance ($\sim$0 m/s) and moved the actuated shoe forward at a linear speed of 1 m/s. The controller boxes received signals through a remote controller operated by the experimenter. All software for the controller boxes and the remote controller were written in Python. Details on the control software are published in (Zhang, 2017) and a detailed description of the motorized shoes will be revealed in the full utility patent (currently in provisional status). The split-belt group did not wear the motorized shoes and walked with their regular shoes on an instrumented split-belt treadmill (Bertec, Columbus, OH, United States).



Split-belt			*Motorized Shoes*				
Net Speed	=	*Treadmill Speed*	*Net Speed*	=	*Shoe Speed*	+	*Treadmill Speed*
Slow = 0.5 m/s	=	0.5 m/s	*Slow = 0.5 m/s*	=	1 m/s (forward)	+	1.5 m/s (backward)
Fast = 1.5 m/s	=	1.5 m/s	*Fast = 1.5 m/s*	=	0 m/s (locked)	+	1.5 m/s (backward)
Medium = 1 m/s	=	1 m/s	*Medium = 1 m/s*	=	0 m/s (locked)	+	1 m/s (backward)

Figure 17: (A) A motorized shoe involving proprietary technology was used to induce adaptation in the motorized shoes group. (B) Schematic of the motorized shoe. This consists of a motor, a controller box, a gearbox, two toothed timing belts, and four rubber wheels. (C) Mean time courses for foot speed across participants for the motorized shoes and the split-belt groups. The white background indicates experimental epochs of "tied" walking when both feet moved at the same speed, whereas the gray background indicates the epoch of "split" walking when the dominant leg moved three times faster than the non-dominant leg. The table summarizes the procedure used to set the slow, fast, and medium speeds for each foot. The same procedure was used in all epochs. It is worth pointing out that the treadmill always moved at 1.5 m/s during adaptation in the motorized shoes group. The speed difference between feet was achieved by locking the wheels on the fast side and moving the slow foot forward at 1 m/s to obtain a net speed of 0.5 m/s on the slow side. Of note, the foot's speed on the fast side was slightly slower on the motorized shoes than the split-belt group.

4.2.3 General Paradigm

All participants adapted following a conventional sensorimotor adaptation paradigm that consisted of three walking conditions: baseline, adaptation, and post-adaptation (Figure 17C, Top). During these periods, participants' feet moved at one of three possible speeds: slow

(0.5 m/s), medium (1 m/s), or fast (1.5 m/s). The implementation of these speeds is displayed in Figure 1C. Participants in the motorized shoes group wore these shoes throughout the experimental protocol, whereas participants in the split-belt group wore regular sneakers. Thus, the net foot speed in the motorized shoes group was the sum of the treadmill's speed (moving the foot backward) and the shoe's speed (moving the foot forward), whereas the foot speed in the split-belt group was only dependent on the treadmill's speed (Figure 17C, Bottom). For example, in the motorized shoes group the slow foot speed (0.5 m/s) resulted from the combined effect of the treadmill moving the foot at 1.5 m/s (backward) and the motorized shoe moving the foot at 1 m/s (forward) (i.e. 1.5 m/s − 1 m/s = 0.5 m/s). The motorized shoes were OFF and wheels were locked (0 m/s) at the fast and medium speeds; thus, the foot's net seed at those velocities was only determined by the treadmill's speed. This was done to maximize the experiment's duration for a given battery life. Our approach also enabled us to implement the same feet speed's in both groups while participants in the motorized shoes group walked on a regular treadmill (i.e. both belts moving at the same speeds).

A baseline period was collected during which both feet moved at either slow, fast, or medium speeds for 150 strides each (Figure 17C, Top). The baseline behavior during the slow and fast speeds served as a reference for the adaptation condition when the feet moved at different speeds, whereas the medium speed served as a reference for the post-adaptation period when the two feet move at the same medium speed. Moreover, the baseline speed was matched not only in the speed at which the feet moved, but also on how this speed was implemented. For example, in the motorized shoes group, the shoe was actuated in the slow side (net speed = 0.5 m/s) and it was OFF (wheels locked) in the fast side (net speed = 1.5 m/s) during the adaptation period. Accordingly, both motorized shoes were either actuated or OFF in the slow and fast baselines, respectively. The adaptation period lasted 750 strides (approx. 15 min) and the dominant leg (self-reported leg to kick a ball) walked fast. The speed difference and period duration was selected to match other split-belt walking studies showing robust gait adaptation (Sombric et al., 2019). Following the adaptation block, all participants experienced a post-adaptation period of 600 strides during which both feet moved at 1 m/s, which was the average speed of the fast and slow feet. The purpose of this phase was to measure the adaptation effects and its washout when the speed perturbation induced by different devices was removed.

4.2.4 Data Collection

All participants walked on an instrumented treadmill either with or without the motorized shoes, while kinematic and kinetic data were collected to characterize participants' gait. Kinematic data were collected at 100 Hz with a passive motion capture system (Vicon Motion Systems, Oxford, United Kingdom) and kinetic data were collected at 1000 Hz using force plates embedded in the treadmill. Gaps in raw kinematic data due to marker occlusion were filled by visual inspection of each participant in Vicon Nexus software. Positions from the toe (5^{th} metatarsal), ankle (lateral malleolus), knee (lateral epicondyles), and the hip (greater trochanter) were collected bilaterally (Figure 18B). Heel-strikes (i.e. foot landing) and toe-offs (i.e. foot lift off) were identified using the ground reaction force (Fz) perpendicular to the walking surface. More specifically, heel-strike was defined as the instance when $Fz > 30$ N and toe-off as the instance when $Fz < 30$ N. We used this force threshold to have equivalent event detection (i.e. heel strike and toe off) on the treadmill for both groups since each of the motorized shoe weighted 17 N ($\sim$1.7 kg in mass).

4.2.5 Data Analysis

We compared the gait pattern between the motorized shoes and split-belt groups in terms of spatial and temporal symmetry measures that are known to adapt on the split-belt treadmill (Figure 18A; Finley et al. (2015)). Specifically, we used step length asymmetry as a robust measure of adaptation. Step length asymmetry was defined as the difference between step lengths (i.e. distance between ankles) with the slow leg vs. the fast leg (Eq. 4.1). A zero value of step length asymmetry indicated that both step lengths were equal and a positive value indicated that the step length of the fast (dominant) leg was longer than the slow (non-dominant) leg. Step length asymmetry was further decomposed into StepPosition, StepTime, and StepVelocity because these parameters have been shown to be adapted differently during split-belt walking (Finley et al., 2015). The StepPosition quantified the difference in positions of the leading leg (i.e. leg in front of the body) between two consecutive steps (Eq. 4.2). The StepTime quantified the difference in the duration of each of these steps (Eq. 4.3). Lastly, the StepVelocity quantified the difference in the velocities of each foot with respect to the body for these two steps (Eq. 4.4). Since participants take steps with different sizes, we normalized the differences in step length, StepPosition, StepTime, and StepVelocity by their stride length, quantified as the sum of two step lengths. This allowed us to avoid inter-subject variability. For visualization purposes, these parameters were smoothed with a five-step running average.

$$Step\,length\,asymmetry = \frac{FastStepLength - SlowStepLength}{SL} \tag{4.1}$$

$$StepPosition = \frac{(\Delta\alpha_{fast} - \Delta\alpha_{slow})}{SL} \tag{4.2}$$

$$StepTime = \frac{\frac{v_{slow}+v_{fast}}{2} * (t_{slow} - t_{fast})}{SL} \tag{4.3}$$

$$StepVelocity = \frac{\frac{t_{slow}+t_{fast}}{2} * (v_{slow} - v_{fast})}{SL} \tag{4.4}$$

In these equations, $\Delta\alpha_i$ indicates the difference between each foot's position (i.e. ankle marker) and the body (i.e., mean position of the two hip markers) at ipsilateral heel strike (Figure 18A); In addition, t indicates the step time defined as the duration between the heel-strike of ipsilateral leg to the contralateral leg; and v indicates the step velocity quantified as the relative velocity of the foot with respect to the body. When walking on the treadmill, v_{slow} and v_{fast} approximated the speeds of the slow and fast belt, respectively. Therefore, StepVelocity was mostly reflective of belt speed difference, rather than participants' behavior. Finally, note that all measures were normalized by each participant's stride length (SL, sum of both step lengths) to account for inter-subject differences in step sizes.

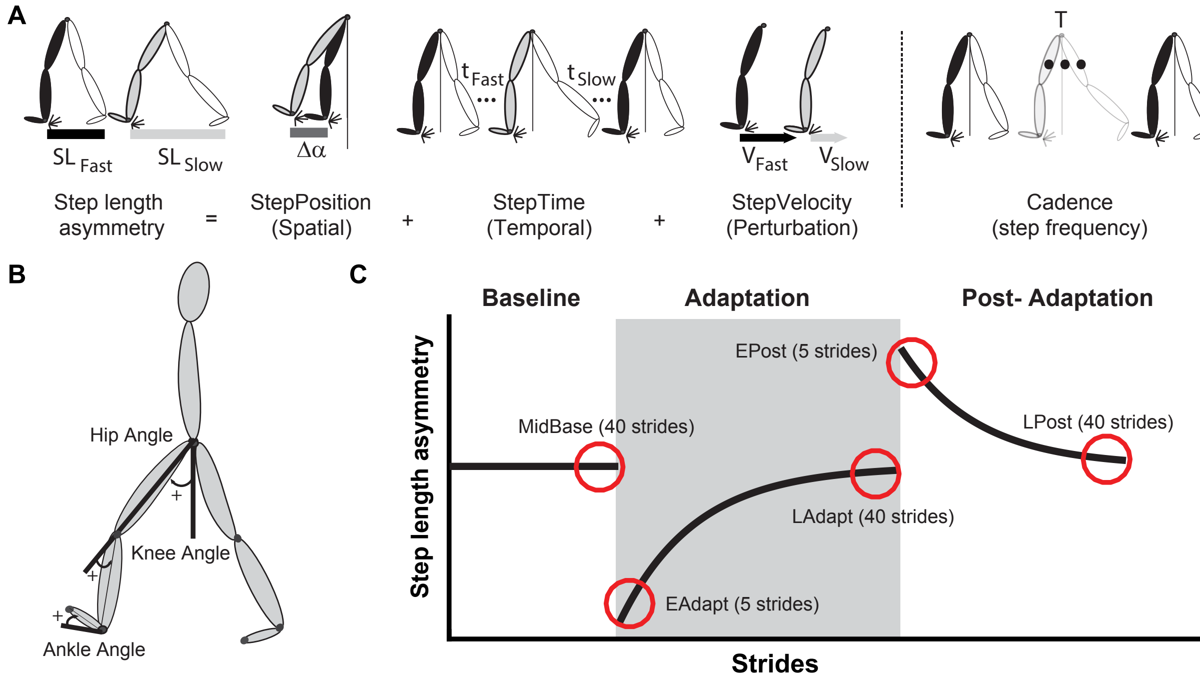


Figure 18: A) This schematic illustrates Step length asymmetry and its decomposition into StepPosition, StepTime, and StepVelocity. Step length asymmetry is quantified as the difference between fast and slow step lengths, normalized by stride length. The equation and decomposition are explained in detail in the methods section of this manuscript. In brief, (StepPosition) differences between the fast (black leg) and the slow (gray leg) leading leg's positions contribute to step length asymmetry. Similarly, differences in the trailing leg's positions (white legs) also contribute to step length asymmetry. The trailing leg's position depends on step time and step velocity. Consequently, differences in step times (tfast and tslow) or step velocity (Vfast and Vslow) leads to step length asymmetry. We also show a schematic of Cadence, which is computed as the inverse of the gait period (T). B) Illustration of reflective marker positions and joint angle conventions. C) Epochs of interest are illustrated by the red circles placed over a schematic of step length asymmetry. Shaded gray area represents the adaptation period when the feet move at different speeds ("split" walking), whereas white areas represent when the feet move at the same speed.

We also computed joint angles and cadence to determine the impact of the motorized shoes on each foot's motion and step frequency. Ankle, knee, and hip angles were computed on the sagittal plane (2D) to directly contrast our results to previous reports of joint angles during split-walking (Reisman et al., 2005). Joint angles were calculated such that flexion/dorsiflexion was positive and extension/plantarflexion was negative (Figure 18B). We also defined all angles to have value of 0° at the neutral standing position (i.e., full extension for knee and hip and approximately 90° angle between shank and foot for the ankle). More specifically, ankle angles were calculated as the angle between the foot (ankle marker to toe marker vector) and the shank (ankle marker to knee marker vector) subtracted from each participant's neutral position (i.e., mean and standard deviation: $88.4° \pm 3.7°$ for the group wearing the motorized shoes and $91.2° \pm 0.95°$ for the split-belt group). Knee angles were calculated as the angle between the shank and the thigh (knee marker to hip marker vector) subtracted from 180°. Lastly, we computed the hip angles as the angle between the thigh and the vertical unit vector. Angle data was time-aligned and binned to compute mean angle values over 6 intervals of interest during the gait cycle. This was done to focus on changes in angles within the gait cycle, rather than on changes due to differences in cycle duration across the distinct walking conditions (Dietz et al., 1994; Reisman et al., 2005). More specifically, we computed averaged angle values over 6 phases of interest (Perry J, 2010): Double support (DS1, DS2), Single stance (SS1, SS2), and the swing phases (SW1, SW2). Double support during early stance (DS1) was defined as the period from heel strike to contralateral toe off. Single stance (from contralateral toe-off to contralateral heel strike) was divided into 2 equal phases (SS1, SS2). Double support during late stance (DS2) was defined as the interval from contralateral heel strike to ipsilateral toe off. Finally, the swing phase (from ipsilateral toe-off to ipsilateral heel-strike) was divided into 2 equal phases (SW1, SW2). Joint angles were assessed in 8 participants per group since the remaining 2 participants (one per group) was missing essential marker data. Lastly, we computed cadence (i.e. number of strides per second) to determine if this gait feature was altered by wearing the motorized shoes.

4.2.6 Outcome Measures

Each gait parameter was analyzed during four experimental epochs of interest (early adaptation, late adaptation, early post-adaptation, and late post-adaptation) to compare the adaptation and after-effects between the motorized shoes and the split-belt treadmill groups. We computed the averaged value of each parameter over these epochs as follows. First, we removed the five strides at the beginning and at the end of each trial to eliminate effects of holding on to the handrail when starting and stopping the treadmill. This was done to characterize people's movement when no individuals were holding on to the safety rail. Then, we computed the average value for each epoch as follows: early adaptation (EAdapt, average of five strides: 6^{th}–10^{th} stride), late adaptation (LAdapt, average of 40 strides: 706^{th}– 745^{th} stride), early post-adaptation (EPost, average of five strides: 6^{th}–10^{th} stride), and late post-adaptation (LPost, average of 40 strides: 546^{th}–595^{th} stride) (Figure 18C). All of the parameters were corrected by any baseline biases (MidBase, average of 40 strides: 106^{th}–145^{th} stride). EAdapt gave us information about the induced perturbation by the "split" condition, while the LAdapt provided information regarding the steady-state behavior at the end of the adaptation trial. The behavior during EPost was quantified to assess how much participants adapted to the new walking pattern (e.g. after-effects). Finally, we assessed LPost behavior to ensure that participants returned to their baseline walking behavior (e.g. washout). Moreover, we used joint angle measures to determine the effect of the motorized shoes on the overall gait pattern. This analysis was intended to determine if participants were actually walking with the motorized shoes (i.e. not dragging their feet or sliding their feet). To this end, we computed the averaged value over the last 40 strides (after removing the very last five strides, as in the other kinematic parameters) for each one of the four experimental epochs of interest (i.e. SBase, FBase, MidBase, and LAdapt).

4.2.7 Statistical Analysis

We performed one-sample Kolmogorov-Smirnov tests to determine if each parameter (i.e., Step length asymmetry, Step lengths, StepPosition, StepTime, StepVelocity, and Cadence) was normally distributed in every epoch of interest (i.e., EAdapt, LAdapt, EPost, and LPost). We found that all parameters were normally distributed, thus we ran separate two-way repeated measures ANOVAs to test the effects of epochs and groups (i.e., Motorized shoes vs. Split-belt) on each of our gait parameters. Statistical analysis were done with unbiased data (i.e., MidBase was subtracted from all the epochs) to focus on changes that occurred beyond those due to distinct group biases. In case of significant main or interaction effects, we used Fisher's post-hoc testing to determine whether values were different between groups. We chose this post-hoc testing to be more sensitive to potential group differences. Lastly, we performed a one-sided one sample t-test to determine whether early post-adaptation values were different from zero. This was done to determine if after-effects were significant in each group. Comparisons between post-adaptations values across groups were only done when we found significant interactions between group and epoch.

Two separate multiple linear regressions were performed to determine if the individual variation in 2 independent variables: 1) StepPosition and 2) StepTime in late adaptation could be predicted by two regression coefficients and their interaction: group (categorical factor), StepVelocity (continuous variable), and group#StepVelocity (interaction). We also performed two separate multiple linear regressions to determine if the individual variation in after-effects in StepPosition and StepTime (2 independent variables) were predicted by group or each respective steady state (StepPosition LAdapt or StepTime LAdapt). This was done because we observed speed differences between the groups (Figure 17C - Top) that could impact the extent of adaptation and after-effects on spatial and temporal measures.

Joint angles were compared across groups using unpaired t-test for each of the gait phases. We reasoned this was an appropriate statistical test to compare the behavior across groups given that joint angles are highly temporally correlated within the gait cycle and spatially correlated across segments. We subsequently corrected the significance threshold for each epoch using a Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995), setting a false discovery rate of 5% (FDR correction). The reason for choosing this correction was due to higher number of comparisons that we made.

A significance level of α =0.05 was used for all statistical tests. Stata (StataCorp., Collage Station, TX), was used to perform the ANOVAs, whereas MATLAB (The MathWorks, Inc., Natick, MA, United States) was used for all other analyses.

4.3 Results

4.3.1 Motorized Shoes Can Induce Robust Sensorimotor Adaptation of Locomotion

Our results show that the motorized shoes were able to induce similar adaptation of step length asymmetry compared to the split-belt treadmill. Specifically, there were no significant group ($F_{(1,48)} = 0.21$, $p = 0.65$) or group by epoch interaction effects ($F_{(3,48)} = 1.26$, $p = 0.29$) on the adaptation of step length asymmetry, indicating that this parameter was similarly modulated throughout the experiment between the Motorized shoes and Split-belt groups (Figure 19A). We observed a significant main effect of epoch ($F_{(3,48)} = 94.91$, $p < 0.001$) in step length asymmetry and found that both groups had significant after-effects (Motorized shoes: $p < 0.001$; Split-belt: $p < 0.001$; Figure 19A). While modulation of step length asymmetry was indistinguishable between groups, we observed small differences in the adaptation of the fast leg's step length. Specifically, we found a group by epoch interaction effect in the fast step length ($F_{(3,48)} = 3.18$, $p = 0.032$; Figure 19B) driven by between-group differences during the early adaptation phase ($p = 0.012$). While significant, this between-group difference might not be meaningful given that the values that observed in both groups fall within the range of those previously reported (Sombric et al., 2019). Moreover, after-effects in this parameter were significant in the Motorized shoes group ($p = 0.013$), but not in the Split-belt group ($p = 0.15$). In contrast, the adaptation of the slow leg's step length was similar across groups throughout the experiment (group: $F_{(1,48)} = 0.63$, $p = 0.44$; group by epoch interaction: $F_{(3,48)} = 0.69$, $p = 0.49$; Figure 19C). We only found a significant epoch effect on slow step length ($F_{(3,48)} = 70.47$, $p < 0.001$) and substantial after-effects in both groups (Motorized shoes: $p < 0.001$; Split-belt: $p <0.001$). In summary, fast leg's step length exhibited small differences between the Motorized shoes and Split-belt groups that did not impact the adaptation of step length asymmetry, which was indistinguishable between these groups.

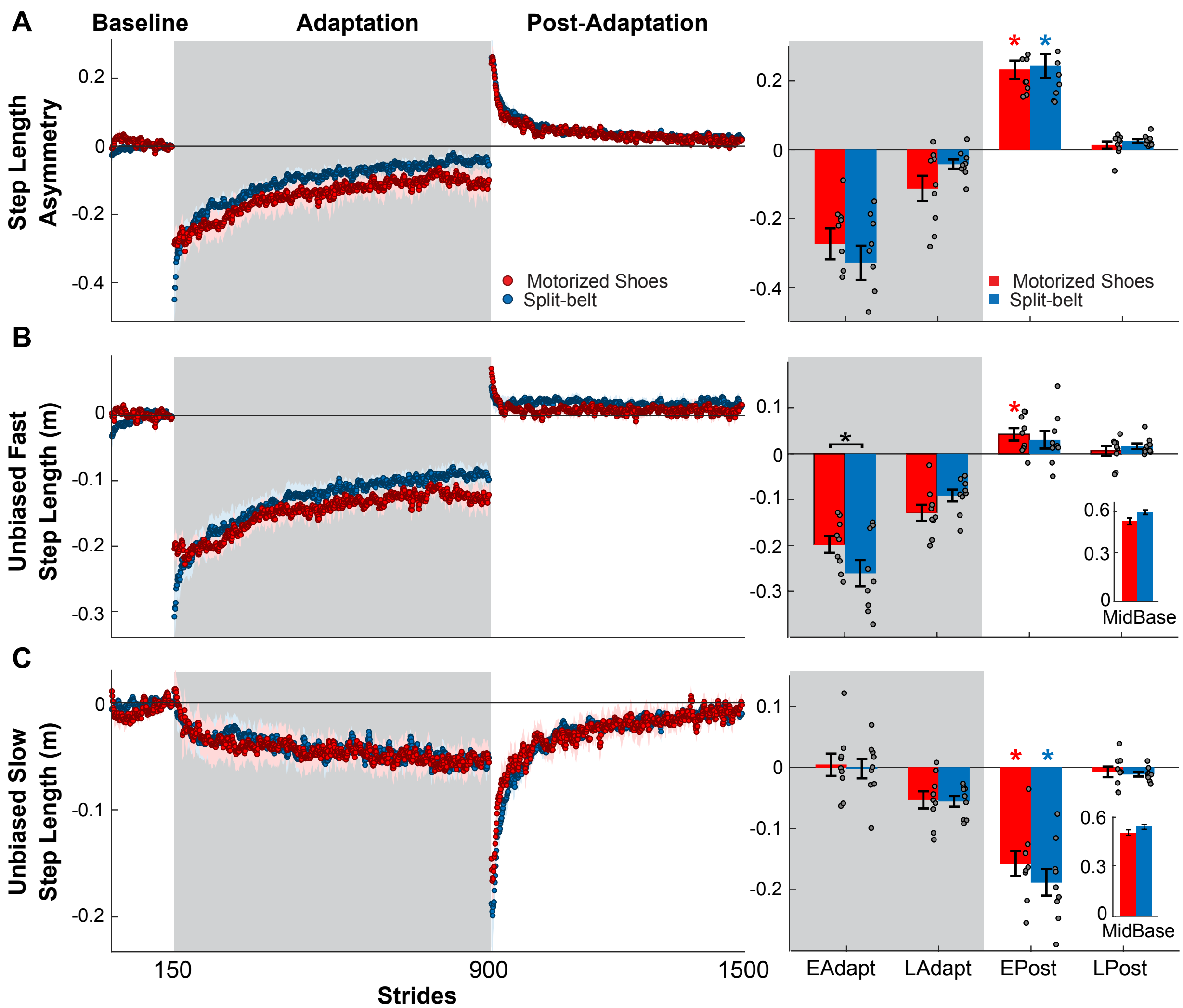


Figure 19: Modulation of step length asymmetry and step lengths. (A, B, C- Left Panel) Time courses for step length asymmetry and individual step lengths during medium baseline, adaptation and post-adaptation. Shaded gray area represents the adaptation period when the feet move at different speeds ("split" walking), whereas white areas represent when the feet move at the same speed. Colored dots represent the group average of 5 consecutive strides and colored shaded regions indicate the standard error for each group (Motorized shoes: red; Split-belt: blue). (A, B, C- Right Panel) Bar plots indicate the mean ± standard errors for step length asymmetry and step lengths for each group and epoch of interest. Note that the reported step lengths are unbiased. This was done by subtracting the averaged step length values during baseline at medium speed in each participant. Significant differences for post-hoc tests were indicated as follows. Black asterisks over the bracket above each epoch represent statistical significant differences between the Motorized shoes and the Split-belt groups ($p < 0.05$). Colored asterisks over the bars indicate significant after-effects (i.e., early post-adaptation is significantly different from baseline; $p < 0.05$) for each of the groups (Motorized shoes: red; Split-belt: blue). The small bar plots on the right indicate the mean ± standard errors for the step lengths for each group during medium baseline.

4.3.2 Smaller Speed Difference With the Motorized Shoes Reduced the Adaptation of StepPosition

We observed between-group differences in the adaptation of StepPosition (quantifying spatial asymmetry), but not StepTime (quantifying temporal asymmetry). This was indicated by the significant group by epoch interaction found in StepPosition ($F_{(3,48)} = 3.47$, $p = 0.023$), but not in StepTime ($F_{(3,48)} = 2.39$, $p = 0.09$) (Figure 20). Post-hoc analyses indicated that these differences in StepPosition were driven by distinct early and late adaptation values of this parameter in the Motorized shoes group compared to the Split-belt group (early adaptation: $p = 0.031$; late adaptation: $p = 0.036$). Yet, after-effects in StepPosition were significant in both groups (Motorized shoes: $p < 0.001$; Split-belt: $p < 0.001$) and after-effects in StepTime were only significant in the Motorized shoes group (Motorized shoes: $p = 0.017$; Split-belt: $p = 0.087$) Interestingly, we also found a group effect ($F_{(1,48)} = 6.58$, $p = 0.021$) on StepVelocity and a group by epoch interaction trending effect ($F_{(1,48)} = 2.78$, $p = 0.051$) (Figure 20C). In particular, the StepVelocity was smaller in the group with Motorized shoes than in the Split-belt group during late adaptation ($p = 0.001$), which we thought could impact the motor adaptation of the Motorized shoes group. Thus, we performed multiple linear regression analysis on the late adaptation epoch with either StepTime or StepPosition as the dependent variable and StepVelocity as the predictor. StepVelocity was indeed related to StepTime ($R^2 = 0.59$; $p = 0.005$; StepTime = -1.19 * StepVelocity - 0.32) and StepPosition ($R^2 = 0.55$; $p = 0.009$; StepPosition = -0.82 * StepVelocity - 0.15). However, individual StepVelocity values were only a predictor of StepTime values (Group: p_group = 0.19, Regression coefficient = 0.44, %95 CI = [-0.25,1.13]; StepVelocity: p_velocity = 0.001, Regression coefficient = -1.99, %95 CI = [-3.08,-0.91]; Interaction: p_group#velocity = 0.16, Regression coefficient = 1.14, %95 CI = [-0.49,2.78]), whereas the relation between StepVelocity and StepPosition was driven by a group effect (Group: p_group = 0.047, Regression coefficient = 0.71, %95 CI = [0.0092,1.4]; StepVelocity: p_velocity = 0.068, Regression coefficient = -1.01, %95 CI = [-2.1,0.086]; Interaction: p_group#velocity = 0.069, Regression coefficient = 1.5, %95 CI = [-0.13,3.16]) (Figure 20D). We also found that the inter-subject variability in steady-state values was not associated to individual after-effects in neither StepPosition ($R^2 = 0.23$; p = 0.29), nor StepTime ($R^2 = 0.12$; p = 0.59) (Figure 20E). To sum up, the reduced speed difference in the Motorized shoes group limited the adaptation of StepPosition, but we still observed group after-effects with the motorized shoes in the spatial and temporal domains.

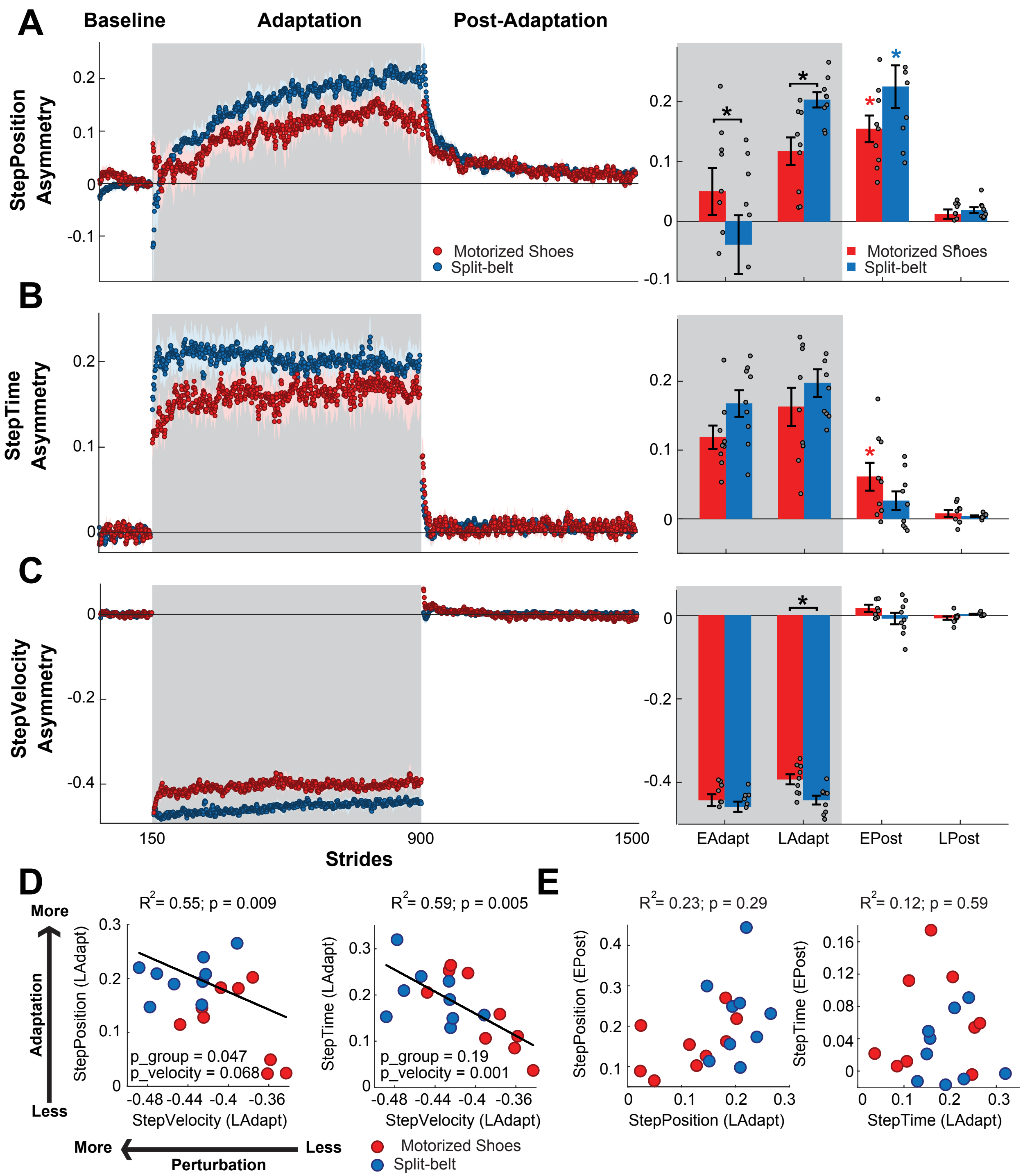


Figure 20: Adaptation of spatiotemporal components of step length asymmetry. (A, B, C- Left Panel) Time courses for StepPosition, StepTime, and StepVelocity before, during and after adaptation. Shaded gray area represents the adaptation period when the feet move at different speeds ("split" walking), whereas white areas represent when the feet move at the same speed. Colored dots represent the group average of 5 consecutive strides and colored shaded regions indicate the

standard error for each group (Motorized shoes: red; Split-belt: blue). (A, B, C- Right Panel) The bar plots indicate the mean ± standard errors for StepPosition, StepTime, and StepVelocity for each group and epoch of interest. Gray dots represent individual participants. Note that the values were corrected for baseline biases. Significant differences for post-hoc tests were indicated as follows. Black asterisks over the bracket above each epoch represent statistical significant differences between the Motorized shoes and the Split-belt groups ($p < 0.05$). Colored asterisks over the bars indicate significant after-effects (i.e., early post-adaptation is significantly different from baseline; $p < 0.05$) for each of the groups (Motorized shoes: red; Split-belt: blue). D) Scatter plots illustrate the association between the StepVelocity at steady state and either the StepPosition or StepTime at steady-state during adaptation (i.e., LAdapt). We present the p-values for the multiple regression model (p), for the continuous variable (StepVelocity, p_velocity) and for the categorical variable (group, p_group). E) Scatter plots illustrate the association between the LAdapt and EPost for StepPosition and StepTime. No significant relations were observed for neither StepPosition nor StepTime.

4.3.3 Similar Cadence Is Observed Between the Groups Throughout the Experiment

We found that the motorized shoes did not alter the modulation of cadence throughout the experiment compare to split-belt walking (Figure 21 - left). Specifically, there were no significant group ($F_{(1,48)} = 0.02$, $p = 0.88$) or group by epoch interaction effects on cadence ($F_{(3,48)} = 0.32$, $p = 0.81$), indicating that the adaptation and after-effects of cadence were similar between groups (Figure 21 - right). We also found that both groups exhibited increased cadences during early post-adaptation compared to baseline (Motorized shoes: $p = 0.002$; Split-belt: $p = 0.003$). In sum, individual wearing the motorized shoes modulate cadence similarly to individuals in the Split-belt group.

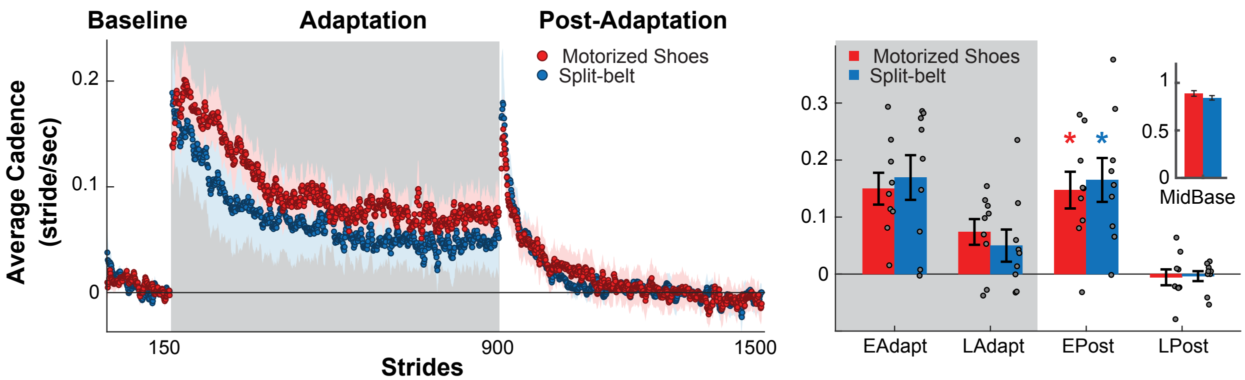


Figure 21: Modulation of cadence. (Left Panel) Time courses during medium baseline, adaptation and post-adaptation for the average cadence is shown for each group. Shaded gray area represents the adaptation period when the feet move at different speeds ("split" walking), whereas white areas represent when the feet move at the same speed. Colored dots represent the group average of 5 consecutive strides and colored shaded regions indicate the standard error for each group (Motorized shoes: red; Split-belt: blue). (Right Panel) Bar plots indicate the mean ± standard errors for cadence for each group and epoch of interest. Note that the values were corrected for baseline biases (i.e., MidBase). Colored asterisks over the bars indicate significant after-effects (i.e., early post-adaptation is significantly different from baseline; $p < 0.05$) for each of the groups (Motorized shoes: red; Split-belt: blue). The small bar plot on the right indicate the mean ± standard errors for the Cadence for each group during medium baseline.

4.3.4 Effect of Wearing Motorized Shoes on Gait Kinematics

Overall, the gait pattern with and without the motorized shoes was similar. Figure 22A illustrates the joint angles over the gait cycle for the ankle, knee, and hip joints for the group wearing the motorized shoes (red) and the group wearing regular shoes (blue) during medium baseline walking. We found joint angles were the same between groups for most phases of the gait cycle, in which significance was determined with an FDR controlling procedure (18 comparisons, $p >$ Pthreshold, Pthreshold $= 0.0055$, see methods) (Figure 22A). There were only a few differences in specific phases of the gait cycle. Specifically, the Motorized shoes group demonstrated reduced ankle dorsiflexion following ipsilateral heel strike and during late swing (double support DS1: $p = 0.004$, effect size $= 3.3°$; late swing SW2: $p = 0.004$, effect size $= 4.1°$). Moreover, the Motorized shoes group exhibited reduced knee flexion compared to the Split-belt group during early swing (SW1: $p = 0.004$, effect size = 7.8°), followed by slightly more knee extension in late swing (SW2: $p = 0.001$, effect size = 9.6°). Lastly, the Motorized shoes group had larger hip flexion during stance of baseline walking ($p = 0.005$, effect size = 4.1°). While these between-group differences were significant, they should be interpreted consciously given the reliability of kinematic measurements. Namely, one can find significant changes in joint angles that are greater than 5° when measured across sessions within the same cohort of healthy, young participants (Wilken et al., 2012). Therefore, the differences that we find, ranging from 3.3° to 9.6°, might not be meaningful. In addition to baseline joint kinematics, we also compared late adaptation kinematics across groups (Figure 22B). Specifically, we contrasted the changes in joint angles during late adaptation relative to the speed-specific baseline for each of the six phases of the gait cycle. We found no differences between the groups (36 comparisons, $p >$ Pthreshold), suggesting that joint angles were modulated similarly in the split condition with the motorized shoes or the split-belt treadmill. Thus, our results demonstrated that walking with the motorized shoes had only minor effects on joint kinematics and did not alter the adaptation of individual joint angles during split walking.

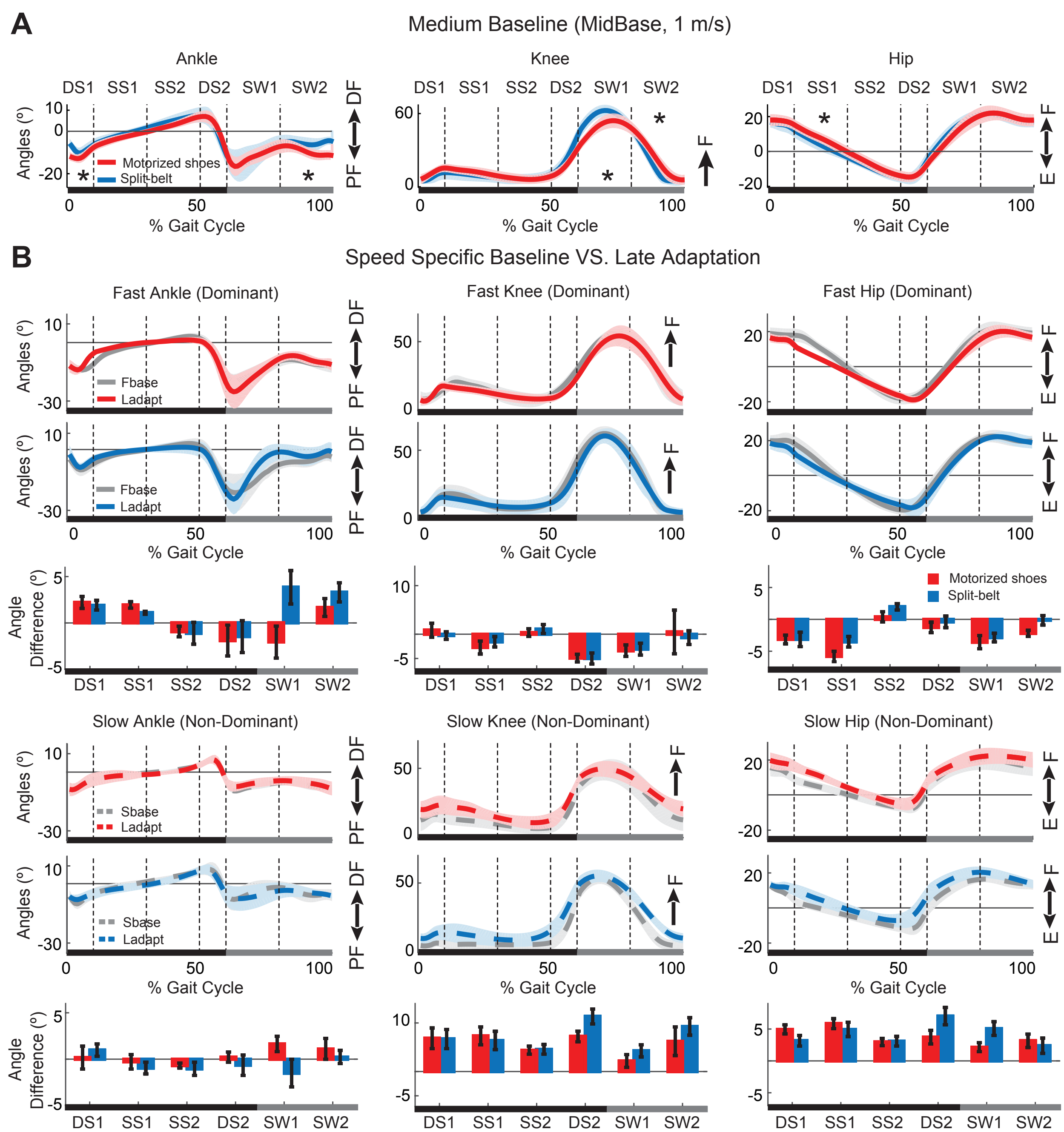


Figure 22: Joint angles over the gait cycle during baseline and adaptation A) Baseline joint angles are shown for the group walking with regular sneakers (i.e., blue trace) and the group walking with the Motorized shoes (i.e., red trace). Solid lines represent the group average and shaded areas represent standard errors. Asterisks indicate instances during the gait cycle when joint angles were significantly different across groups. The overall motion for all joints was similar across groups, but hip flexion, knee flexion and ankle dorsiflexion were smaller when wearing the motorized shoes. B) Speed specific baseline (gray) and steady-state angle trajectories during adaptation for the Motorized shoes (red) and the Split-belt (blue) groups. Solid lines represent the motion of the leg

walking fast in the split condition (colored lines) and in the fast baseline (gray) condition. The dashed lines represent the motion of the leg walking slow in the split condition (colored lines) and in the slow baseline (gray) condition. The bars represent the change from the speed specific baseline to late adaptation in joint angles during different phases of the gait cycle. DS: Double support; SS: Single Stance; SW: Swing; DF: dorsiflexion; PF: plantarflexion; F: flexion; E: extension.

4.4 Discussion

4.4.1 Summary

We investigated if a pair of motorized shoes could induce split-like locomotor adaptation. We found that the adaptation effects induced by the motorized shoes moving at different speeds were as robust as those observed with a split-belt treadmill. Moreover, we found that the gait pattern was largely similar between walking with the motorized shoes or on the split-belt treadmill. Specifically, step length asymmetry, cadence, and step lengths were similar across groups during and after the split condition with either device. We only observed subtle differences in individual joint angles during the baseline condition with the motorized shoes compared to walking with regular shoes, which might be due to the greater height and weight of the motorized shoes. Taken together, our results suggest motorized shoes can induce robust sensorimotor adaptation in locomotion, opening the exciting possibility to study locomotor learning under more realistic situations outside the laboratory setting.

4.4.2 Similar Walking and Adaptation With Split-Belt Treadmill and With Motorized Shoes

We demonstrated that the motorized shoes can induce locomotor adaptation largely similar to the adaptation induced with the split-belt treadmill. This was shown by the comparable adaptation across groups of gait parameters, such as step length asymmetry, and the same modulation of joint angles from baseline to adaptation for both groups. Namely, the initial and steady state values during the split condition for the split-belt group and motorized shoes group were consistent with values previously reported for joint angle kinematics (Winter, 1987; Reisman et al., 2005) and asymmetries in step length (Malone and Bastian, 2010; Finley et al., 2015), step position (Sombric et al., 2017), and step time (Gonzalez-Rubio et al., 2019). We found between-group differences in the fast step length during early adaptation, such that participants with the motorized shoes placed the fast leg closer to the body. This distinct behavior might also be explained by the fact that the balance is perturbed in the beginning of the split condition (Buurke et al., 2018; Iturralde and Torres-Oviedo, 2019) and it might be further challenged when stepping with the motorized shoes by augmenting the center of mass' height, increasing even further gait instabilities while walking. However, this between-group differences might not be very meaningful and should be interpreted cautiously given than the range of these step length values fall within those previously reported (Sombric et al., 2019).

Participants with the motorized shoes reached lower steady state values of StepPosition (spatial) and slightly lower steady state values of StepTime (temporal) relative to the split-belt group. Our multiple regression analysis indicated that smaller speed differences (i.e., perturbation) were predictive of smaller steady state values for StepTime, but not StepPosition. Thus, perturbation size regulated the extent to which participants adapted in our temporal measure, as observed in other sensorimotor adaptation protocols of reaching (Morehead et al., 2015; Marinovic et al., 2017) or walking (Finley et al., 2015; Yokoyama et al., 2018). We did not find a direct relation between perturbation size and the reached steady state of StepPosition at an individual level, indicating that there are other factors, such as navigation strategies (Matthis et al., 2017) or practice (Day et al., 2018), influencing "where" people place their feet. Despite the subtle differences during adaptation, we saw similar after-effects between groups during early post-adaptation in all gait parameters. For example, cadence exhibited comparable changes between the groups during early adaptation and early de-adaptation, which is consistent with previous literature showing that stride time (i.e., inversely related to cadence) decreases in the beginning of adaptation (Reisman et al., 2005) and post-adaptation (MacLellan et al., 2014). In summary, our portable device induced significant adaptation and after-effects of gait asymmetries in space and time opening the door for studying locomotor adaptation outside of the laboratory.

We did not find a direct correspondence between adaptation and after-effects in neither the spatial nor the temporal domains. The positive relation between steady state values and after-effects is commonly found in reaching or saccadic movements with well-defined performance errors (Chen-Harris et al., 2008). This relation between steady-state values during the adaptation period and after-effects is, however, elusive in split-belt protocols. For example, gait parameters such as StepTime asymmetry, can change dramatically during the Adaptation period (i.e., split condition) without showing any significant after-effects (Long et al., 2015; Gonzalez-Rubio et al., 2019). A recent study has also shown that changes in motor patterns during steady state split-belt walking and post-adaptation are not related and might be mediated by different neural substrates (de Kam et al., 2020). Taken together our findings further support the idea that gait adjustments during and after split-belt walking are governed by different mechanisms.

4.4.3 Study Implications

We found a few differences in joint motions when walking with our motorized shoes during regular walking, which will be useful for future designs of this portable device. Notably, we observed gait changes during baseline walking (i.e., both feet moving at the same speed) with the motorized shoes that were consistent with other studies showing that shoe weight (Ochsmann et al., 2016) and height (McDonald et al., 2019) alter walking movements. In addition, the rigidity of the motorized shoes' soles (Chiou et al., 2012) is another factor that might contribute to the differences that we observed in joint angles during baseline walking. Thus, our gait analysis enabled us to identify key shoe features that we will modify to reduce the effect of the motorized shoes on the regular walking pattern. This is important because contextual differences when wearing the motorized shoes could limit the extent of generalization of movements from walking with them to walking without this portable device. Locomotor adaptation with the motorized shoes overground could certainly reduce context specific difference that limit the generalization of treadmill movements, such as visual flow (Torres-Oviedo and Bastian, 2012), walking speed (Dingwell et al., 2001), and step initiation.

However, it remains to be determine whether contextual cues due to the height, weight, and rigidity of the motorized shoes would also limit the generalization of locomotor learning with them.

It is worth emphasizing that both groups were tested on a treadmill. This was done to track the movements of participants throughout the experiment, which we could not do with the motorized shoes outside the laboratory. Nevertheless, our results are promising because body-worn sensors, also referred to as wearables, now provide an inexpensive opportunity for the continuous monitoring of ambulatory activity in free-living environments (Wang and Adamczyk, 2019), which is a match to our technology. The actuation of the motorized shoes can add up to 1 m/s to the speed of each foot. Thus, we are certain that we can evoke speed differences comparable to split-belt studies (Reisman et al., 2005; Sombric et al., 2019) with this motorized shoes while walking over ground. In sum, the combination of these technologies can enable gait adaptation studies in realistic settings outside the laboratory. However, future studies with systems including adequate sensing mechanisms are needed to test this possibility.

Our results are also exciting because this portable device could also offer the possibility to study gait under more realistic situations, such as walking with self-regulated and variable gait speeds. It is well-accepted that motor variability can impact motor learning (Wu et al., 2014; Ulman et al., 2019), and walking on a treadmill is less variable compared to overground walking (Dingwell et al., 2001). Thus, having a device that can induce locomotor adaptation overground would help us gain more understanding about the relationship between variability and motor adaptation in walking. Moreover, learning a new task involves generation of new neural activity patterns, which appears after several days of practice (Oby et al., 2019). Our device will enable training over longer periods of time because individuals will be able to train at home and gain much more practice in the altered split environment than what is currently available. This can help us contribute to recent efforts to investigate the effect of long-term practice (Hardwick et al., 2019).

There have been efforts to develop portable rehabilitation devices (Handzic et al., 2011; Afzal et al., 2015; Lahiff et al., 2016; Calabrò et al., 2018) and assistive devices (Rao et al., 2008; Awad et al., 2017; Bae et al., 2018) to improve walking patterns in individuals with gait asymmetries, such as individuals post-stroke. While these apparatus could reduce the metabolic cost associated to gait in this clinical population (Awad et al., 2017) and improve walking speed (Rao et al., 2008; Buesing et al., 2015; Calabrò et al., 2018), these devices were unsuccessful in modifying the step length asymmetry (Handzic et al., 2011), which is an important parameter in rehabilitation of post-stroke patients (Patterson et al., 2008, 2014). For example, Lahiff and colleagues were able to modify push-off and breaking forces, but their device was unable to change step length of the participants (Lahiff et al., 2016). Similarly, Handzic and colleagues designed a device to passively induce a speed difference between the feet (Handzic et al., 2011; Handzic and Reed, 2013). However, this passive device induced limited changes in step length asymmetry post-adaptation (i.e., $\sim 5\%$ of the after-effect size observed with the split-belt treadmill and motorized shoes). In sum, our study indicates that motorized shoes could tackle previous limitations altering gait asymmetries with portable devices and thus, could be potentially used to correct asymmetric steps post-stroke.

5.0 Conclusions

Generalization is the human ability to transfer movements from trained to untrained environments. This dissertation identified various factors and provided tools that impact and improve the generalization of movements in locomotor adaptation. Specifically, factors such as age, error size, the extent of adaptation, and the similarity between the training and the testing conditions were assessed in the first two aims. Aim 3 introduced a device that can enhance the similarities between the training and testing settings to improve the generalization in locomotion.

Healthy aging rather than experienced error size during adaptation modulates the generalization of movements from the training to the testing environment. The work presented in Aim 1 suggested that healthy aging would result in difficulty switching patterns and leading to a larger generalization of the recalibrated movements from the training to the testing contexts. This finding is consistent with previous literature in walking (Sombric et al., 2017) and reaching (Fernández-Ruiz et al., 2000; Bock and Girgenrath, 2006; Heuer and Hegele, 2008) adaptation. These age-related changes in motor perseveration can be explained by the degeneration of basal ganglia as we age. We know that the basal ganglia are responsible for motor switching (Brown and Almeida, 2011; Leunissen et al., 2013; Balser et al., 2014). This means that the age-related structural (Wolpe et al., 2020) and functional (Bäckman et al., 2006; Ota et al., 2006; Walhovd et al., 2011) changes in the basal ganglia can lead to poor motor switching and greater motor perseveration. We also know that healthy aging results in higher motor (Kallio et al., 2012; Vanden Noven et al., 2014) and sensory (Zhang et al., 2008; Goble et al., 2009; Maheu et al., 2015) noise, lead to the reduction of sensed error and updating their internal representation (Wolpert et al., 1995). This means that older adults tend to attribute the sensed errors to their own movements (Kelly and Sober, 2014); therefore, having difficulty switching their motor patterns across different conditions (Sombric et al., 2017; Sombric and Torres-Oviedo, 2021). Taken together, our results show that older adults have a harder time switching and disengaging their motor patterns when facing a new environment compared to young adults. On the other hand, we found that error size does not affect the generalization of movements from the training to the testing environment. One explanation might be the presence of catch during the adaptation. Previous studies have shown that when participants are exposed to a certain type of perturbation they acquire a "new normal" throughout the adaptation and removing that perturbation is similar to experiencing the perturbation in the opposite direction (Herzfeld et al., 2014; Iturralde and Torres-Oviedo, 2019). Therefore, experiencing catch (i.e., removing the perturbation) can help participants practice the motor pattern switching and therefore exhibiting poor aftereffects overground. Finding no error size effect on generalization is at odds with previous literature showing greater generalization with the gradual adaptation in both young adults (Torres-Oviedo and Bastian, 2012) and post-stroke patients (Alcântara et al., 2018). These distinct findings might be due to methodological differences as the participants were adapted with different speed differences (0.5 vs 0.75) during adaptation and we know that speed differences play an important role in motor adaptation (Leech et al., 2018). Taken together, our results suggest that older adults generalize their movements from the training to the testing environment regardless of the error size experienced during adaptation; however, this may not be the case for young adults.

Not only age impacts the generalization of movements, but also the similarity between the training and the testing environments is a very important factor. Aim 2 revealed that more contextual similarity between the training and the testing environments would lead to larger generalizations in the kinematic measures. This was shown by our results that participants in the flat group (i.e., more similar to the testing condition) generalized more compared to the incline group (i.e., more different to the testing condition). We know from previous literature that incline walking has different contextual features (i.e., braking and propulsion forces) compared to flat walking (Lay et al., 2006, 2007). We also know that decreasing contextual similarity would lead to poor generalization (Ahmed et al., 2008; Ingram et al., 2010; Torres-Oviedo and Bastian, 2010; Hirashima and Nozaki, 2012) while increasing contextual similarity enhances generalization (Tulving and Thomson, 1973; Spear, 1978; Bouton et al., 1999). This means that our data is consistent with previous literature showing larger generalization in the flat (i.e., more similar to the testing environment) group compared to the incline (i.e., less similar to the testing environment) group in the kinematic measures. Our findings of the generalization are at odds with previous literature showing that more adaptation would lead to more generalization in visuomotor tasks (Hewitson et al., 2020). This is because the assessment of the generalization happened in the same context in the visuomotor task (i.e., training in one direction but testing in multiple directions within the same environment) while we assessed generalization of similar movement (i.e., walking) from one environment (i.e., treadmill) to another environment (i.e., overground). In summary, our results suggest that contextual similarity is more important than the extent of adaptation in the generalization of movements in locomotor adaptation.

Finding out that contextual similarity between the training and testing is a key feature in the generalization of movements, it would be beneficial to have a device to overcome contextual differences between the treadmill (training) and overground (testing) locomotion. To further investigate the importance of contextual similarity (i.e., the similarity between training and testing contexts) on the generalization of locomotor adaptation, I used a pair of motorized shoes that could increase the similarity between walking with the device (training context) and walking without it (testing context). Therefore, I tested the feasibility of using this pair of motorized shoes to induce locomotor adaptation like the split-belt treadmill. We found that the adaptation effects induced by the motorized shoes moving at different speeds were as robust as those observed with a split-belt treadmill. This is promising because locomotor adaptation with the motorized shoes overground could certainly reduce context-specific differences that limit the generalization of treadmill movements, such as visual flow (Torres-Oviedo and Bastian, 2012), walking speed (Dingwell et al., 2001), and step initiation. In sum, our study indicates that motorized shoes could tackle previous limitations altering gait asymmetries with portable devices and thus could be potentially used to do gait training.

This dissertation not only provided new insights into the factor impacting the generalization of sensorimotor adaptation but also introduced a new tool to assess the generalization in a more naturalistic environment to possibly improve it. We saw that age is one of the important factors that affect the generalization of movements. This means that rehabilitation strategies should consider age-related differences while using an intervention to improve the quality of life of patients. Also, we observed that the similarity between the training and the testing environments can significantly enhance the generalization. This suggests that training centers can benefit from increasing the similarity between their settings and real-life situations to maximize the outcome of their interventions. We also provided tools that can improve the similarity between the treadmill and overground walking that can be used in gait training. Taken together, this dissertation provided understating about the generalization of movements from trained to untrained contexts that can be used in rehabilitation and training.

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