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Gait asymmetries are a common problem for clinical populations—such as stroke survivors and people with Parkinson's disease—and are associated with increased gait instability and fall risk. Current methods to alter gait asymmetries rely heavily on split-belt treadmill training. Gait training using visual cues projected on a screen or in immersive virtual reality have been shown to produce greater improvements in gait asymmetries relative to traditional treadmill training alone. However, it is unclear the extent to which gait asymmetries can be systematically altered using an asymmetric visual cue, which represents a more cost-effective strategy relative to split-belt treadmill training or immersive virtual reality. Investigating whether using a visual asymmetric cue can alter gait symmetry in healthy adults is the first step in determining if this methodology is plausible for future research with clinical populations. The purpose of this dissertation was threefold: (1) to examine the extent to which healthy adults can synchronize to an asymmetric visual cue during treadmill walking; (2) to explore if the asymmetric walking pattern is retained once the visual cue is removed; and (3) to examine transfer of the asymmetric walking pattern to overground walking after the treadmill training session. Seventy-two healthy participants (age 23.89 ± 6.08 years) were enrolled in this study and quasi-randomized into four experimental groups (N = 64) or the control group (N = 8). All participants completed questionnaires related to health history/demographics, limb dominance, and physical activity. All groups completed three 10-minute walking sessions with wearable sensors (APDM Inc., Portland, OR) to record spatiotemporal gait measures. The first session was the same for all groups and consisted of walking at their self-selected speed on the treadmill. For session two, experimental groups 1 and 2 attempted to synchronize their gait to a visual cue (i.e., walking

stick figure) exhibiting a small gait asymmetry presented on the projection screen in front of that treadmill, while experimental groups 3 and 4 attempted to synchronize their gait to a visual cue with a large gait asymmetry. For the third session, groups 1 and 3 walked on the treadmill for 10 minutes after the visual cue was removed, while groups 2 and 4 walked for 10 minutes overground after the treadmill training.

The dependent variables were calculated using the Symmetry Index (SI) equation: stride length SI %, step duration SI %, and single limb support SI %. Visually inspecting the data showed some participants responded to the visual cue stimulus, while others did not. Therefore, experimental groups were further divided into responders (N = 42) and non-responders (N = 22). Wilcoxon Signed Rank and Mann Whitney U tests were run to determine if the gait asymmetry metrics differed from baseline to adaptation, adaptation to post adaptation and between groups, and Wilcoxon effect sizes were calculated to determine the magnitude of the effect. The results reported in Manuscript I show gait asymmetries increased in the small and large asymmetry responder groups; the effect sizes were moderate to large. However, no changes were shown in the small and large asymmetry non-responder groups; the effect sizes were small to moderate. The results from Manuscript II show that the small asymmetry responder group has reduced gait asymmetries during retention, yet some gait asymmetry metrics remain elevated in the large gait asymmetry responder group during retention. The gait asymmetry responder groups revealed decreases in almost all gait asymmetry metrics indicating the adopted gait pattern did not transfer to overground walking. No gait asymmetry changes were observed for the non-responder groups for retention or transfer. Collectively, the results suggest that an asymmetric visual cue can be used to alter gait symmetry and retention may be observed as such training. However, further research should investigate why some participants did not respond to the visual cue.

ALTERING GAIT SYMMETRY USING AN ASYMMETRIC VISUAL CUE

by

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DEDICATION

Dedicated to my husband, mentors, family, and friends. Thank you for believing in me because without all of you this would not have been possible. To Chris, thank you for your understanding and mentorship over the last four years. To my husband, thank you for your unwavering love and support, and constant encouragement.

APPROVAL PAGE

This dissertation written by Krista Grace Meder has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I: INTRODUCTION

Gait asymmetries, defined as the bilateral differences of the lower extremity during walking, are associated with decreased weight bearing, increased gait instability and fall risk (Jørgensen et al., 2000a; Lewek et al., 2014; Wei et al., 2017). Falls are a major public health concern as more than 25% of adults ages 65 and older fall per year (Bergen, 2016) and nearly 20% result in serious injury such as broken bones (Alexander et al., 1992; Sterling et al., 2001). Gait asymmetries are a common problem for clinical populations, such as stroke survivors and people with Parkinson's disease. Thus, clinical populations such as poststroke survivors and Parkinson's disease patients are at a greater risk of falling (Axer et al., 2010; Contreras & Grandas, 2012; Wagner et al., 2009). Current methods to alter gait asymmetries rely heavily on split-belt treadmill training and few studies examined transfer of the gait adaptation task (Fasano et al., 2016; Meder et al., 2022; Nanhoe-Mahabier et al., 2013; Reisman et al., 2005, 2007, 2013; Roemmich, Nocera, et al., 2014; Seuthe et al., 2019).The split-belt treadmill training directly influences the injured limb increasing weight bearing (i.e., to reduce gait asymmetries), which is a primary goal in rehabilitation. An alternative gait training method using visual cues that are projected on a screen or in immersive virtual reality have been shown to produce greater improvements in gait and gait asymmetries than traditional treadmill training alone (Cano Porras et al., 2018; Janeh et al., 2019; Keshner & Lamontagne, 2021).

Synchronization of movement can occur with external cues such as another human, avatars, and auditory metronomes (Meerhoff et al., 2019; Rhea et al., 2014; Soczawa-Stronczyk & Bocian, 2020). Interpersonal synchronization can occur when two people walk side by side, face front to back or face to face. Synchronization between two individuals can be intentional (i.e., cued) or spontaneous. Intentional synchronization can produce greater synchrony than spontaneous synchronization. Intentionally synchronizing to a human and an avatar in an immersive environment produces similar results suggesting both methods are effective (Soczawa-Stronczyk & Bocian, 2020).

It is unclear the extent to which gait asymmetries can be systematically altered using an asymmetric visual cue, which represents a more cost-effective strategy relative to split-belt treadmill training or immersive virtual reality to target reducing gait asymmetries. Transfer of gait adaptation training is a critical motor learning principle that is lacking in the gait rehabilitation literature. Investigating whether using an asymmetric visual cue can alter gait symmetry in healthy adults is the first step in determining if this methodology is plausible for future research with clinical populations. A series of experiments are presented in three manuscripts to address the gaps. The aims and associated hypotheses for each manuscript are presented below:

Manuscript I

Aim 1: Examine the extent to which healthy adults could synchronize to an asymmetric visual cue during a 10-minute treadmill walking session with asymmetric gait ratios: 1.4-1 (small asymmetry) and 1.9-1 (large asymmetry).

- Hypothesis 1: Participants would exhibit an asymmetric walking pattern when synchronizing to the 1.4-1 ratio and 1.9-1 ratio. Participants in the 1.9-1 ratio group would exhibit greater stride length asymmetry, step duration asymmetry, and single limb support asymmetry compared to the 1.4-1 ratio group.

Manuscript II

Aim 2: Explored if the asymmetric walking pattern was retained once the visual cue was removed during a 10-minute treadmill walking session after the initial training session.

- Hypothesis 2a: Participants would retain stride length asymmetry, step duration asymmetry, and single limb support asymmetry for 10 minutes.
- Hypothesis 2b: Participants in the 1.9-1 ratio group would exhibit greater gait asymmetry than the 1.4-1 ratio group during the retention period.

Aim 3: Examined transfer of the asymmetric walking pattern to overground walking after the treadmill training session in a 10-minute period after the initial training session.

- Hypothesis 3a: Participants would exhibit stride length asymmetry, step duration asymmetry, and single limb support asymmetry for 10 minutes during overground walking.
- Hypothesis 3b: Participants in the 1.9-1 ratio group would exhibit greater gait asymmetry than the 1.4-1 ratio group during overground walking.

CHAPTER II: REVIEW OF THE LITERATURE

Overview

This literature review introduces gait and coordination in healthy participants as well as clinical populations. Next, this review discusses gait synchronization that is intentional or spontaneous and how external cues can alter synchronization. Subsequently, this review discusses gait impairments, specific information on the history of gait symmetry and asymmetry and the various training to alter gait asymmetries. Then, locomotor adaptations were discussed in terms of methodology and specific gait adaptations. Furthermore, the applicability of visual information, and motor learning principles in gait adaptation will be discussed. Finally, a discussion on the gaps in literature with regard to this dissertation was presented.

Gait in Healthy Adults and Clinical Populations

Gait and Coordination

Gait can be defined in several ways such as (1) a method of locomotion involving alternating both legs to provide support and propulsion with one foot in contact with the ground at all times, and (2) a series of rhythmic, alternating movements of the limbs and trunk which results in forward progress of the center of gravity (Whittle, 2007). Gait can also be defined as the manner or style of walking (i.e., walking pattern) (Whittle, 2007). Gait can be measured for varying durations of time and is often divided into gait cycles to distinguish left and right gait metrics.

In healthy adults, the gait cycle consists of stance and swing phases which account for 60% and 40% of the cycle respectively (Inman, 1966). The gait cycle begins in the stance phase with the initial contact of the heel followed by the loading response, midstance, terminal response and pre swing. The swing phase begins with initial swing (i.e., toe off), mid-swing and terminal swing. The next gait cycle begins with heel contact of the ipsilateral limb. When one limb is in the stance phase, the contralateral limb is in the swing phase (Dietz, 2002; Inman, 1966). Therefore, the bilateral limbs (i.e., interlimb) are coordinated into alternating or anti-phase during locomotion when not in double stance (Dietz, 2002)**.**

Locomotor coordination can be defined as the ability to maintain a phase and context dependent cyclic relationship between different body segments or joints in regard to spatiotemporal parameters (Krasovsky & Levin, 2010). Coordination can be altered using external loads, changes in gait speed and walking patterns, and from disease or injury. Intralimb (i.e., within the same limb) coordination was similar between running and galloping in healthy adults, while distinct differences existed in interlimb (i.e. between limbs) coordination (Whitall & Caldwell, 1992). Altering belt speeds using a split-belt treadmill, so one limb is faster than the other can alter interlimb but not intralimb coordination (Reisman et al., 2005). Another method of altering coordination is through ankle weights. Adding a load to the nondominant leg produces intralimb changes with the loaded limb, no changes with the unloaded limb, while most of the adaptations were with interlimb coordination (Haddad et al., 2006). Though some changes in intralimb coordination were seen with unilateral ankle weighting, changes were greater in older women compared to younger women in the braking phase of walking (Byrne et al., 2002). With age, intralimb and interlimb coordination of gait worsens (Byrne et al., 2002; Krasovsky et al., 2012; Plotnik et al., 2007) and further worsens with disease or injury such as Parkinson’s disease and stroke (Plotnik et al., 2007; Tseng & Morton, 2010). Poststroke survivors have the greatest interlimb coordination differences during the swing phase (Combs et al., 2013). Greater interlimb coordination changes could indicate that intralimb coordination may be more stable with adaptations (Haddad et al., 2006; Whitall & Caldwell, 1992). The changes primarily with interlimb suggest the neuromuscular system has preferred rates of locomotion according to the task, which may be dependent on energy requirements (Whitall & Caldwell, 1992). Alterations in gait and coordination can be produced through synchronization of movement with external cues.

Synchronization

Synchronization of gait can occur when two people walk together, typically when walking side by side, which is referred to as interpersonal synchronization. For two people to stay near each other when walking they must coordinate their movements with the other person, and step length and cadence will vary to reach the destination together (Zivotofsky & Hausdorff, 2007). However, interpersonal synchronization can be an unintentional or intentional process.

Unintentional or spontaneous synchronization is when a person synchronizes to an external cue or another person (i.e., interpersonal synchronization) without conscious awareness. It is well known that unintentional synchronization frequently occurs between two individuals walking together (Nessler et al., 2013; Nessler & Gilliland, 2009; Zivotofsky & Hausdorff, 2007). Unintentional in phase synchrony begins as soon as visual information is exchanged (Oullier et al., 2008). Zivotofsky and Hausdorff (2007) discovered that with qualitative observations of middle school-aged girls who walked in pairs without synchronization instructions, they were in synchrony nearly 50% of the time. Tactile feedback (i.e., handholding) produced the largest amount of synchrony compared to auditory, visual and no feedback conditions (Zivotofsky & Hausdorff, 2007). Regardless of the sensory feedback condition, unintentional synchronization was still observed between the walking pairs (Zivotofsky & Hausdorff, 2007). Similar results were produced with side-by-side treadmill walking using visual, auditory, and tactile cues while also examining leg length differences on synchrony. The smaller the difference in leg length between partners, the greater the synchrony (Nessler & Gilliland, 2009). Also, for partners with similar leg lengths, synchrony was present even in the absence of one sensory system (i.e., if vision was blocked, participants will use auditory information) and was not different than when both sensory systems were available (Nessler & Gilliland, 2009). Walking side by side on a treadmill compared to overground walking produced similar results as half of the paired partners unintentionally synchronized (Nessler & Gilliland, 2010).

Interpersonal synchronization can be intentional when people are instructed to synchronize to an external cue such as another person. Zivotofsky and colleagues (2012) examined if people could be instructed to walk side by side and intentionally synchronize movements with another person. The greatest synchronization occurred when the auditory, visual, and tactile feedback were all available. Less synchronization occurred with only tactile feedback available, followed by auditory and then visual feedback with the lowest synchronization scores. Similar to their previous findings on unintentional synchronization (Zivotofsky & Hausdorff, 2007), Zivotofsky et al. (2012) reported that only 50% of the pairs walked synchronously. However, intentional compared to unintentional synchronization can decrease step length and increase swing velocity (Nessler & Gilliland, 2010). Other external cues can be used for intentional synchronization. In Parkinson’s disease patients, rhythmic auditory stimulation increased gait speed, stride length and swing time (Hausdorff et al., 2007). Also, the increases in the gait characteristics persisted immediately and 15 minutes after the rhythmic auditory stimulation was removed showing retention of gait adaptation (Hausdorff et al., 2007) When walking was auditorily cued in people with Parkinson’s disease at different percentages related to their cadence, gait improved in velocity and steadiness (Brodie et al., 2015). However, several participants with high freezing of gait scores mentioned difficulty with the auditory cued walking.

Interpersonal coordination or interpersonal synchronization can occur when two people are not walking side by side. For instance, when two people are walking towards each other in a cross walk and must navigate a path to avoid colliding and therefore must coordinate with the other person's movements. Walking towards each other, a follower was instructed to maintain a specific distance with the leader to assess movement coordination, in which step length varied depending on whether the role of the person is leader or follower, and the follower exhibited decreased step length (Ducourant et al., 2005). Initial distance of where the follower started walking in reference to the leader influenced step velocity. The farther the follower was from the leader, the greater the decrease in step velocity. However, the leader's step velocity was always greater than the follower regardless of the initial distance (Ducourant et al., 2005). The coordination between the pairs of individuals happened on a global and not local level as the follower coordinated their movements with the leader, while both people had different leading segmental movements (Ducourant et al., 2005). Marmelat et al. (2014) examined synchronization between a leader and a follower in which the follower was instructed to synchronize with the leader. The followers were able to synchronize heel strikes to the leader's heel strikes using self-paced, and isochronous and fractal metronomes (Marmelat et al., 2014).

An alternate method arose for cuing interpersonal coordination and synchronization using avatars. Meerhoff et al. (2014) examined distance regulation using the leader and follower design in two conditions: a humanoid avatar and a sphere, which were projected onto a screen. While participants were effective in both conditions, synchronization was more accurate and response times were shorter with the avatar (Meerhoff et al., 2014). Spatial accuracy was less accurate when the leader and follower were facing each other compared to when the follower was facing the back of the leader (Meerhoff et al., 2017). Meerhoff et al. (2019) further examined distance regulation with avatar appearance and motion. An avatar was created using motion from a participant to act as the leader; the participants that acted as the followers were told to maintain the distance from the avatar and underwent multiple trials with the avatar in different appearances (Meerhoff et al., 2019). Spatial accuracy was highest when the avatar appeared with segmental motion (i.e., when the avatar appeared as humanoid and as point-light from the retro-reflective markers) compared to when the cadence of the avatar’s motion was constrained, and when only global information was provided without any motion animation (Meerhoff et al., 2019). No differences existed in spatial accuracy between the avatar and point-light appearance (Meerhoff et al., 2019). Soczawa-Stronczyk and Bocian (2020) investigated interpersonal coordination with an avatar in an immersive virtual environment in overground walking. Stride length was lower in the virtual environment compared to real world; however only in the side-by-side walking with the avatar and not the front-to-back walking (Soczawa-Stronczyk & Bocian, 2020). The real world person, who acted as the pacer, had higher stride frequency than the participants, but less of a difference in stride frequency existed with instruction to synchronize to the pacer (Soczawa-Stronczyk & Bocian, 2020). Walking in pairs without instructions to synchronize produced low synchronization strength indices that did not meet the threshold for synchrony in pairs. However, walking in pairs with instructions to synchronize produced indices that exceeded the synchronization strength threshold for real world walking and in the virtual environment (Soczawa-Stronczyk & Bocian, 2020).

Synchronization of a fractal metronome and auditory cues to stepping and walking can alter fractality, which is the self-similar movement across multiple scales of measurement (e.g., stride-to-stride variability) (Hausdorff et al., 1997). Healthy adults were able to adapt to both a more random and more persistent fractal pattern (Marmelat et al., 2014; Rhea, Kiefer, D'Andrea, et al., 2014; Rhea, Kiefer, Wittstein, et al., 2014; Roerdink et al., 2015). Fractality can also be altered in older adults (Kaipust et al., 2013) and in diseases such as Parkinson's disease (Hove et al., 2010). Younger and older adults can retain the adapted fractal pattern after training (Rhea, Kiefer, Wittstein, et al., 2014; Vaz et al., 2020). Healthy, active young and older adults have similar gait fractal dynamics with preferred walking and asymmetric walking, but older adults exhibited less fractality with slow walking (Ducharme et al., 2019). However, healthy systems are highly complex, so a loss of complexity can indicate an abnormal or disease state (Lipsitz, 2002). A loss of complexity indicates a loss in adaptive capacity reducing functional mobility (Lipsitz, 2002). Older adults and people with Huntington's or Parkinson's disease all exhibit greater variability in stride to stride fluctuations during gait than healthy controls indicating less long range correlations (Hausdorff et al., 1997, 1998).

Gait Impairments with Aging and Disease

In a healthy locomotor system, visual, vestibular and somatosensory feedback along with input from the motor cortex, basal ganglia, and cerebellum are necessary for appropriate movement. In clinical populations, damages to the brain can impair movement (Li et al., 2021; Teasell & Hussein, 2013). Strokes cause damage to the cerebral hemispheres and brainstem. Motor impairments depend on the side of the lesion affected and whether the lesion is in the cerebral hemispheres or brainstem (Teasell & Hussein, 2013). Two major problems after stroke are spasticity and hemiparesis leading to gait impairments (S. Li, 2017). Gait velocity is a good indicator for assessing function and recovery after stroke (Schmid et al., 2007). However, gait asymmetries are a better indicator of motor recovery than gait velocity (Brandstater et al., 1983).

Parkinson’s disease (PD) is caused by a loss of neurons in the substantia nigra pars compacta, a part of the basal ganglia, that leads to dopamine deficiencies (Dauer & Przedborski, 2003). The loss of dopaminergic neurons is responsible for the disease’s major motor problems, especially of coordination (Dauer & Przedborski, 2003). Parkinson’s disease causes difficulty initiating movement, tremors, and freezing of gait (Giladi et al., 2001; Mazzoni et al., 2012). Freezing of gait occurs in approximately 50% of the people with PD (Giladi et al., 2001; Mazzoni et al., 2012), and the severity of symptoms in Parkinson’s disease is associated with greater impairments (Giladi et al., 2001).

Age, stroke, and Parkinson’s disease are associated with cognitive decline in areas such as information processing speed and executive function (Dauer & Przedborski, 2003; Deary et al., 2009; Delbaere et al., 2010; Mack & Marsh, 2017; Teasell & Hussein, 2013). Clinical populations and older adults are at an increased risk of falling and becoming injured (Axer et al., 2010; Maki, 1997; Schwartz et al., 2005). Older adults, individuals poststroke and those with Parkinson’s disease exhibit slower walking speeds, shorter step lengths, greater stride interval variability, gait asymmetries and increased support time compared to younger adults (Haworth, 2008; Maki, 1997; Patterson et al., 2008, 2012).

In clinical populations, gait asymmetries are a main target of rehabilitation programs. The consequences of developing gait asymmetries are increased metabolic cost, gait instability, muscular imbalances and bone mass density loss (i.e., from decreased weight bearing), which lead to lower activity levels and increased fall risk (Jørgensen et al., 2000b; Patterson et al., 2008; Sánchez & Finley, 2018). More than 25% of adults 65 years and older fall per year (Bergen, 2016), thus, falls are a major health concern as they result in a decreased ability to live independently and early mortality for older adults (Alexander et al., 1992; Kuzuya et al., 2006).

Gait Asymmetries

Gait was assumed to be symmetric in healthy individuals with ‘normal’ gait. Assuming symmetry simplified data processing and analyses, as data collection would only occur on one limb. Gait symmetry has been defined as having (1) perfect agreement between the actions of the lower limbs, (2) no statistical difference in bilateral parameters, or (3) when the lower extremities behave identically (Sadeghi et al., 2000). Sadeghi et al. (2000) reviewed the literature on symmetry in healthy adults reporting mixed results on whether gait asymmetry exists in spatiotemporal, kinematic, and kinetic parameters. Joint motion symmetry was seen in the frontal, transverse, and sagittal plane of the hip and in the sagittal plane of the knee using an electrogoniometer during walking (Hannah et al., 1984). Menard et al. (1992) found no asymmetries in ground reaction forces during walking. Researchers also examined electromyographic (EMG) activity and reported participants had symmetric or almost perfectly symmetric EMG of the lower limbs during walking (Arsenault et al., 1986; Carlsöö et al., 1974) and different walking velocities (Pierotti et al., 1991). However, some studies only examined the dominant limb or pooled the results of both sides as gait symmetry was assumed (Sadeghi et al., 2000).

On the contrary, Herzog et al. (1989) showed that in 62 healthy adults not one had perfectly symmetrical ground reaction forces bilaterally, providing evidence that gait asymmetries exist in healthy adults’ gait. Symmetry indices were low for vertical and anterior-posterior ground reaction forces deviated less than four percent from zero (i.e., little asymmetry existed) (Herzog et al., 1989). Although large symmetry indices existed for mediolateral ground reaction forces, when the participants completed another experiment by walking on the force plate one way for half the time and then the opposite direction the symmetry indices were much closer to zero (Herzog et al., 1989). However, large variations in symmetry occurred in the anterior-posterior ground reaction forces ranging up to 13 percent (Herzog et al., 1989). Many studies supported the claim that gait is asymmetric in healthy adults for spatiotemporal and kinematic parameters such as step and stride length, foot placement angle, maximum knee flexion and range of motion (Sadeghi et al., 2000). It was postulated that these gait asymmetries exist in healthy adults due to the behavior of the lower limbs, as Hirasawa (1981) suggested that the left and right lower extremities have a supporting and moving function. Hirokawa (1989) reported associations of the right limb with propulsion and the left limb with support. Sadeghi et al. (1997) supported Hirokawa’s (1989) claim; although, all of their participants were right limb dominant, so these roles may be reversed for people who are left limb dominant. While contrasting evidence exists for some gait asymmetry metrics in healthy adults, it could be attributed to small sample sizes and different methods of calculating asymmetries.

Gait velocity was a frequent measure used to assess gait performance after rehabilitation in clinical populations like stroke (Patterson et al., 2008). However, gait velocity did not fully reflect the rehabilitation treatment or outcome goals because another aspect of rehabilitation was improving weight bearing on the paretic limb. Brandstater et al. (1983) suggested that symmetry is a better metric to indicate improvement in motor recovery than velocity alone, as temporal symmetry (e.g., swing/stance phase) and velocity were correlated with motor recovery progression. Thus, the motivation for assessing gait asymmetry is not solely because it is a common gait deficit to occur in pathological gait but that gait asymmetries are a better indicator of functional recovery than gait velocity alone. In addition, improving gait asymmetries is an important clinical rehabilitation goal (Alves et al., 2020; Brandstater et al., 1983; Patterson et al., 2008).

Locomotor Adaptation

Motor adaptation is defined as the process of modifying or adjusting an already well-learned movement or motor skill (e.g., gait) that occurs throughout trial and error practice, when exposing the movement to a novel, perturbing context or environment, resulting in aftereffects (i.e., the adapted behavior remains in the post adaptation period and with practice returns to baseline) (Martin et al., 1996). Adaptive gait can then be similarly defined as the process of modifying gait or locomotive patterns using trial and error practice when exposed to different perturbations or environments. Thus, functional locomotion requires that the limb movements are flexible enough to maintain stability when traversing different environments and changing speed or trajectories (Reisman et al., 2005). A few of the earliest studies examining locomotor adaptation using split-belt treadmills began with healthy adults. Prokop et al. (1995) showed that in healthy individuals, adaptation occurred within 12-15 strides when using a split-belt treadmill, and when the trial was repeated adaptation occurred within 1-3 strides. However, when the condition was reversed (i.e., slow and fast sides were switched) no practice effect was seen and adaption occurred in 12-15 strides (Prokop et al., 1995). As Prokop et al. (1995) only examined very short bouts of adaptation (45 strides), Reisman et al. (2005) investigated interlimb coordination during locomotor adaptation using a single 10-minute session on a split-belt treadmill in healthy adults. Participants were separated into three groups to test three ratios of speed, 2:1, 3:1, 4:1 (Reisman et al., 2005). The protocol began with six minutes of baseline walking at slow and fast speeds with the belts tied before moving into the split-belt condition for 10 minutes. This process was followed by six minutes of post adaptation with the belts tied at slow speed. In the adaptation condition, the fast limb immediately increased in stride length and decreased in stance time, while the slow limb decreased in stride length and increased in stance time. Changes in stance time and stride length were more pronounced in the faster belt conditions, but no other changes were seen during the adaptation period (Reisman et al., 2005). In the post adaptation period, gait metrics returned to baseline with no indication of intralimb aftereffects. The interlimb measures changed slowly during adaptation, and in the post adaptation period had aftereffects before gradually returning to baseline. This study was the first to reveal that healthy adults can adapt a new locomotor pattern in interlimb coordination after adaptation on a split-belt treadmill (Reisman et al., 2005).

Gait adaptation via split-belt treadmill training has also been studied in clinical populations such as people with a history of stroke, Parkinson's disease, and children with hemispherectomy. Reisman et al. (2007) showed that people with a history of stroke respond similarly to the healthy controls with split-belt adaptation. The post-stroke survivors retained their reactive responses to the adaptation and produced aftereffects resulting in an improved gait pattern, specifically in step length and double support time (Reisman et al., 2007). Thus, research indicates the nervous system of patients with a history of stroke can still produce a more normal gait pattern (Reisman et al., 2007, 2009). Reisman et al. (2009) completed another locomotor adaptation in poststroke survivors with similar results that transferred to overground walking. In the overground post adaptation period, a slightly smaller aftereffect was seen compared to the treadmill. When overground, step length returned to baseline within 25 strides for both the stroke and control group. A larger transfer aftereffect from treadmill to overground of double support and step length were seen in the stroke group.

As Parkinson's disease can exhibit a variety of locomotor deficits, Roemmich et al. (2014) investigated locomotor adaptation in Parkinson's disease and older adults. The split-belt adaptation protocol was the same as Reisman et al. (2005). Roemmich and colleagues (2014) reported similar results during the adaptation period as other studies involving poststroke participants, but the initial adaptation was not different between the groups. People with Parkinson’s disease had a significant step length aftereffect during the post adaptation period indicating that the split-belt treadmill training can improve gait in this population (Roemmich, Nocera, et al., 2014). Another study examining locomotor adaptation in Parkinson’s disease also looked at the effects of dopaminergic treatment (Roemmich, Hack, et al., 2014) as the previous study participants performed the sessions in their best-medicated state (Roemmich, Nocera, et al., 2014). Dopaminergic treatment did not affect locomotor adaptation, as both the OFF and ON meds groups exhibited step length aftereffects. No aftereffects were observed in the kinetic measures (e.g., anterior-posterior ground reaction forces) in either group (Roemmich, Hack, et al., 2014).

A traditional single belt treadmill can be used to examine locomotor adaptation in poststroke adults. Savin et al. (2013) used a unilateral weight to resist forward leg motion while participants walked on a treadmill. Participants exhibited aftereffects indicating improved step length. The poststroke individuals had reduced rates of adaptation in the late adaptation period (i.e., took more strides to adapt), while initial adaptation was similar to controls. Other methods have been utilized for locomotor adaptation to improve gait metrics and fall risk such as obstacle crossing.

Obstacle Crossing

Older adults have a greater risk of falling than younger adults, almost 60% of falls result from trips and slips (Berg et al., 1997). Falls from trips typically occur on level or uneven surfaces, but while walking trips occurred due to contact with the obstacles (Berg et al., 1997; Chen et al., 1991). Thus, older adults are at an increased risk of falling with contacting the obstacle (Chen et al., 1991). One way to reduce fall risk is by training individuals to adapt how they walk to successfully avoid obstacles. When an obstacle is in one's pathway, one must either change directions, which isn't often an option, or avoid the obstacle (Patla et al., 1991). In obstacle avoidance training, foot clearance over the obstacle increased in young and older adults (Chen et al., 1991). In stepping over obstacles, nearly 60% of people chose their dominant leg as the leading leg (Chen et al., 1991). Another strategy to avoid obstacles is to change step length by either shortening step length prior to crossing over the obstacle or lengthening step length over the obstacle. The shortening step length strategy is the most common strategy employed, primarily because of the short response time needed to avoid the obstacle (Chen et al., 1994). Older adults initiated changes to the step length one step earlier compared to younger adults (Chen et al., 1994). When more time was given to respond, about 67% of participants chose the lengthening step length strategy (Chen et al., 1994). However, older adults use the shortening step length strategy more frequently than younger adults, and in older adults the lengthening step length strategy was more difficult when crossing over the obstacle (Chen et al., 1994). On the contrary, older females preferred lengthening stride length for most of the trials (Weerdesteyn et al., 2005). The contrasting results were indicated to be due to methodological differences in obstacles, and may not be sex specific as previous studies have found no sex differences between obstacle avoidance strategies (Chen et al., 1991, 1994; Weerdesteyn et al., 2005). However, an early study on obstacle avoidance by Patla and colleagues (1991) supported the claim that step lengthening was the dominant response, although, this study involved younger adults. Also, visual information about the obstacle itself is important to determine the optimal obstacle avoidance strategy (Patla et al., 1991).

Many methods for obstacle avoidance utilized training on a treadmill (Chen et al., 1991; Weerdesteyn, Nienhuis, & Duysens, 2005). Virtual obstacles are a safer alternative to training than with physical obstacles since no actual contact with the obstacle occurs, thus reducing the risk for a fall (Mirelman et al., 2011, 2016). Chen et al., (1994) projected bands of light onto the walkway to create virtual obstacles. Other researchers utilized virtual reality (VR) to implement virtual obstacles as virtual reality provides the opportunity to create any environment without the participant hitting a physical obstacle. Mirelman and colleagues (2016) examined improvements in fall risk with treadmill training and treadmill training with 2D projected virtual obstacles. A decrease in falls occurred within six months with the treadmill and VR group from pre to post training and the rate of falls were lower than in the only treadmill training group (Mirelman et al., 2016). LoJacono and colleagues (2018) investigated 2D VR training on a treadmill and transfer to the real world. The VR obstacle crossing compared to real world obstacle crossing saw increased foot clearance and alterations before and after the real obstacle of foot placement in young and older adults (LoJacono et al., 2018). Lu and colleagues (2019) projected blue stepping stones onto the treadmill, and randomly changed the stones to a red-white striped square to indicate it is an obstacle to avoid. Successfully avoiding the obstacle was associated with the timing of the obstacle appearance (Lu et al., 2019), supporting earlier studies stating higher rates of successfully avoiding obstacles in older adults when the participant had more time to respond (Chen et al., 1994; Weerdesteyn, Nienhuis, & Duysens, 2005). Therefore, clinical populations such as people with Parkinson’s disease need even more time than elderly healthy participants to successfully avoid the obstacle (Lu et al., 2019). The need for increased time for gait adaptions to occur for successful obstacle avoidance in older adults and clinical populations could lead to higher fall risk (Blumen et al., 2020; Lu et al., 2019). Immersive virtual obstacle training in post stroke participants produced greater improvements in gait velocity compared to real world training; however, both methods showed improvements in gait velocity, stride length, walking endurance and obstacle clearance capacity (Jaffe et al., 2004).

Gait Asymmetries

Split-belt treadmill training is a traditional method for studying gait asymmetries and has been utilized by many researchers in a variety of populations (Betschart et al., 2018; Fasano et al., 2016; Lewek et al., 2018; Reisman et al., 2007). The majority of the populations are patients poststroke and a few studies with patients who have Parkinson's disease (Meder et al., 2022). Reisman et al. (2007) completed a study with 13 participants who sustained a stroke more than six months prior and matched controls on locomotor adaptation and symmetry using a split-belt treadmill. The training consisted of two sessions: (1) randomly assigned paretic or non-paretic limb to the fast belt, and (2) contralateral limb was tested on the fast belt. Testing took six minutes for baseline testing at slow and fast speeds with the belts tied, 15 minutes of adaptation, and six minutes post adaptation. Participants were given rest periods (seated or standing) every five minutes in the adaptation period or more as necessary. The training produced asymmetries in the adaptation period and reported aftereffects that temporarily induced symmetry (Reisman et al., 2007). Another study by Reisman et al. (2013) using split-belt treadmill training similar to the previous study in 13 poststroke participants examined gait asymmetry at baseline, immediately post training, and one and three months post training. Step length improved from baseline to post training in about half of the participants, who were considered responders (i.e., if step length asymmetry post training change was greater than the average step length asymmetry at baseline). Step length increased for both legs and a greater increase was seen in the shorter step side, and no changes occurred to temporal measures like stance time asymmetry (Reisman et al., 2013). Betschart and colleagues (2018) used a cohort study of unilateral cerebral stroke survivors to investigate split belt treadmill walking on gait ability poststroke, which was similarly designed to Reisman et al. (2013). Improvements were reported in step length asymmetry after training and these improvements were retained for over a month and comfortable walking speed increased in about half of the participants (Betschart et al., 2018).

Lewek and colleagues (2018) utilized motor learning strategies to augment and minimize errors in split-belt treadmill training in poststroke participants. Error augmentation occurred by increasing the velocity of the belt if the stance time was shorter on the paretic limb and error minimization decreased the belt. Participants were randomly assigned into three groups: augmentation, minimization or control, and divided into whether they had spatial or temporal asymmetries. The training consisted of up to 20 minutes on the split-belt treadmill followed by 10-15 minutes of overground walking. A mixed attentional focus cue was used to increase symmetry (e.g., ride the belt a little longer on your weak side) in all groups. Lewek et al. (2018) reported across all groups that step length asymmetry improved from baseline to post test. Step length asymmetry was still significantly improved at the follow-up test, and there was no difference in asymmetry between posttest and follow-up. Participants who minimized errors tended to reduce their step length asymmetry from pre to post testing, which suggests that minimizing errors does not worsen asymmetry as suspected. Training using minimization versus augmenting errors was not significantly different, so one method was not more effective than the other (Lewek et al., 2018). The use of assistive devices such as a cane or walker was allowed during training in several studies (Lewek et al., 2018; Reisman et al., 2013), which can affect the training as poststroke participants with baseline asymmetries reduced their asymmetries while walking with a standard cane (Beauchamp et al., 2009).

Parkinson’s disease is another population that has utilized split-belt treadmill training to improve gait asymmetries. In a cross-sectional study of 20 participants with advanced Parkinson’s disease, split-belt treadmill training was used when participants were in the OFF phase of their medication (Fasano et al., 2016). Participants walked for five minutes with the belts tied, then they walked either in the worst side reduction (WSR) condition or best side reduction (BSR). This process was followed by five more minutes of tied belt walking. The WSR was when the leg with the shorter step length was on the slower belt and the BSR was the leg with the longer step length was on the slower belt. The BSR condition improved step length asymmetry during late adaptation and post adaptation, while the WSR increased gait asymmetries (Fasano et al., 2016). Nanhoe-Mahabier and colleagues (2013) explored the effects of split-belt treadmill training on gait asymmetry in people with Parkinson’s disease with a short 2-minute duration of training. All PD participants were in the OFF phase of their medication. Stride length and stride time asymmetries at baseline were larger in the FOG group. During split-belt walking the control and non-FOG groups decreased their stride time asymmetry while the FOG group increased their stride time asymmetry (Nanhoe-Mahabier et al., 2013).

Roemmich and colleagues (Roemmich, Hack, et al., 2014; Roemmich, Nocera, et al., 2014) investigated locomotor adaptation and whether dopamine has an effect on adaptation in Parkinson’s disease patients. Participants underwent split-belt treadmill training similar to Reisman et al. (2005). The PD participants were in the ON phase with their medication. The PD group had larger step length asymmetries, except in early adaptation and post tied condition. All groups had greater asymmetries from baseline to early adaptation. Step length asymmetries during readaptation were not different than late adaptation indicating retention of the learned gait pattern in all three groups. Aftereffects of step length asymmetry in the post tied condition were seen in all groups. The healthy aged matched and younger groups had higher stance time asymmetries in the post-tied condition (Roemmich, Nocera, et al., 2014). When examining the effects of dopamine on adaptation, step length aftereffects were diminished in the OFF phase during de-adaptation, but locomotor adaptation was not effected (Roemmich, Hack, et al., 2014). Mohammadi et al. (2015) investigated different motor tasks and how people with and without freezing of gait (FOG) respond. All participants underwent split-belt treadmill training in six conditions that lasted two minutes each. In the tied belt conditions, the FOG group had larger step length asymmetries at both speeds, and step length asymmetry decreased when increasing speed compared to the non-FOG and control groups. Both PD groups had larger step length asymmetries compared to the control group during the split-belt conditions, and the FOG group's asymmetries were larger than the non-FOG group. Also, the FOG group was slower to adapt, indicating that the severity of freezing influences the ability to adapt to varying speed conditions (Mohammadi et al., 2015).

Visual Information for Gait Adaptation

Vision is critical for providing information about the environment, global information about the body in the environment, and postural and body segment movement (Patla, 1998). Visual information provides regulation of stability during locomotion and for the necessary adaptions needed due to changes in surfaces or terrain in a feedforward manner (Matthis & Fajen, 2014; Patla, 1997). Locomotion is primarily regulated by visual and somatosensory information (Warren, 1995). Visual information, unlike other sensory systems, can provide perceptual information on distance of stationary objects with greater precision and accuracy (Patla, 1997, 1998). Optic flow, which provides self-motion information as well as a three-dimensional layout of a stationary environment, strongly influences the velocity of the body

(Warren, 1995). Optic flow is important as it continuously regulates locomotion through velocity perception (Matthis & Fajen, 2014), which is important for walking in various environments.

Obstacle avoidance relies heavily on visual information. Visual exproprioception is the visual information of the body's position in space in relation to the environment (Schmidt et al., 2019). Visual exproprioception, of the lower limb and the limb's position in the space, is important for altering swing limb trajectory, as obstructing this visual exproprioception alters control of the swing limb and precision of limb placement (Patla, 1998). Alternating foot placement to avoid an obstacle depends on the visual information about the size, shape and location of the obstacle, and on the relationship between the typical foot landing area and the obstacle (Patla et al., 1999). An obstacle must be in view a minimum of two steps prior to crossing to successfully avoid the obstacle (Matthis & Fajen, 2014); although, minimal changes in toe clearance occurred when the last two steps were visible (Patla, 1998). Rietdyk and Rhea (2006) investigated lower limb trajectory of obstacle avoidance with and without lower limb exproprioception. Contact with the obstacle occurred several times with all participants, which were all the trail limb, with half of the contacts occurring with full vision and the other half with the goggles (Rietdyk & Rhea, 2006). When vision was obstructed by the lower limb exproprioception, but positional cues were provided to indicate position of the obstacle, and the horizontal distance prior to the obstacle was the same as full vision without positional cues (Rietdyk & Rhea, 2006). However, stride length and toe clearance over the obstacle increased with using the goggles to reduce contact with the obstacle (Rietdyk & Rhea, 2006). Visual exteroceptive information is important for planning and initiating modifications in stepping patterns prior to crossing (Patla et al., 1991).

Virtual Reality

Virtual reality is a tool that can deliver visual information and evoke responses similar to the real world (Cano Porras et al., 2018; Keshner & Lamontagne, 2021; Soczawa-Stronczyk & Bocian, 2020). Training in virtual reality may entrain areas of the brain involved in motor planning and learning that likely encompass the mirror neuron network (Calabrò et al., 2017). Virtual reality has become a tool for gait and balance interventions as virtual reality shows increased motivation and enjoyment in rehabilitation programs compared to traditional training (Keshner & Lamontagne, 2021), which may improve adherence to the program (Cano Porras et al., 2018). The majority of virtual reality training thus far is with two dimensionality using screens or monitors to depict the virtual environment and treadmills, referred to as non-immersive (Calabrò et al., 2017; Canning et al., 2020; Cano Porras et al., 2018; LoJacono et al., 2018). Immersive and non-immersive virtual reality training are both effective techniques to improve gait, balance and mobility: however, immersion in virtual reality may further enhance training due to feeling a sense of presence and embodiment (Keshner & Lamontagne, 2021).

Populations such as poststroke survivors, patients with Parkinson's disease, Multiple Sclerosis, Cerebral Palsy and traumatic brain injuries have benefitted from virtual reality training (Cano Porras et al., 2018). Improvements in balance, mobility, obstacle crossing and spatiotemporal gait measures such as walking speed and stride length were seen with virtual reality rehabilitation programs (Cano Porras et al., 2018; Corbetta et al., 2015; de Rooij et al., 2019; Jaffe et al., 2004; LoJacono et al., 2018; Mirelman et al., 2011, 2016). However, whether training outcome transfer to the real world and the influence of the level of immersion on the outcomes remains unknown (Cano Porras et al., 2018).

Gait and Virtual Reality

Treadmill and Virtual Reality

Virtual reality training on a treadmill is typically non-immersive. The virtual environment is projected on a monitor while participants walk on a treadmill (Calabrò et al., 2017; LoJacono et al., 2018; Mirelman et al., 2016). Gait adaptations are necessary for obstacle avoidance training; obstacle avoidance training in virtual reality is used as a safer method for older adults and clinical populations. Lu and colleagues (2019) used virtual stepping stones as obstacles while walking on a treadmill for training in Parkinson's disease patients. Another obstacle crossing intervention in virtual reality used a virtual environment with feet projected on the screen. The obstacle appeared in the foreground and moved closer at the preferred speed of the participant, which gave around 30 seconds before stepping to avoid the obstacle (LoJacono et al., 2018). Mirelman and colleagues (2016) used a similar approach with the feet appearing in the virtual environment that is on the screen in front of the participant while walking on a treadmill; while virtual obstacles were in the environment, the goal of the intervention was to reduce fall risk and not to improve obstacle avoidance ability. An early virtual reality study with obstacle crossing used an immersive approach through real time view of a camera in poststroke survivors (Jaffe et al., 2004). Parkinson's disease patients, poststroke survivors and younger and older adults who underwent virtual reality training that involved virtual obstacles improved obstacle crossing ability and reduced fall risk (LoJacono et al., 2018; Lu et al., 2019; Mirelman et al., 2016)

Motor performance is improved with the use of virtual reality. Parkinson's disease patients improved gait and mobility after non-immersive virtual reality training on a treadmill compared to treadmill training alone (Calabrò et al., 2017). After non-immersive virtual reality training on a treadmill poststroke survivors improved walking speed, balance and mobility, and improvements were greater with the virtual training than without it (Corbetta et al., 2015). Real time visual feedback of full body kinematics while walking on a treadmill improves trunk and pelvic motion immediately and three weeks after training in a transfemoral amputee (Darter & Wilken, 2011). Non-immersive virtual reality training on a treadmill can improve gait and mobility in older adults and clinical populations.

Gait Synchronization and Visual Information/Virtual Reality

Rhea et al. (2014) examined whether a visual stimulus (i.e., visual metronome) programmed with time series that exhibit persistent or random patterns while walking on a treadmill could alter gait dynamics. The participants were able to synchronize to the fractal visual metronome, which indicated that gait dynamics could be altered in health adults (Rhea, Kiefer, D'Andrea, et al., 2014). It is possible that the fractal visual metronome could be used for gait adaptation in clinical populations. Soczawa-Stronczyk and Bocian (2020) created a virtual environment with an avatar and compared gait coordination in the real environment with a person versus walking in the virtual environment with an avatar. When the participants intentionally synchronized to the other person/avatar, synchronization was higher than unintentional synchronization (Soczawa-Stronczyk & Bocian, 2020). Front-to-back walking consistently produced greater synchronization when compared to side-by-side walking. Synchronization in the virtual environment compared to the real environment produced very similar results (Soczawa-Stronczyk & Bocian, 2020). Segmental and global motion information of a virtual avatar both effectively regulate distance between the participant and the avatar; although, the segmental avatar produced greater timing accuracy (Meerhoff et al., 2014, 2019).

Thus, it is promising as virtual reality has been found to be a motivating tool in rehabilitation, so using a virtual avatar has potential to be beneficial for clinical populations.

Gait Asymmetry and VR

Advancements in technology over the past several decades have produced novel techniques such as virtual reality to improve gait and balance (Cano Porras et al., 2018; Yang et al., 2008). However, studies examining virtual reality (VR) and gait asymmetry without the use of additional methods (e.g., treadmill) are very limited (Janeh, Fründt, et al., 2019; Keshner & Lamontagne, 2021; Shideler et al., 2021). Janeh and colleagues (2019) investigated how visual and proprioceptive signals in virtual reality conditions can alter asymmetry in Parkinson's diseases patients experiencing freezing of gait. In the ON phase of medication, participants walked on a GAITRite mat while immersed in virtual reality. Only the proprioceptive-visual dissociation (i.e., shifting the foot backward in virtual reality) condition improved step length asymmetry (Janeh, Fründt, et al., 2019). Shideler and colleagues (2021) investigated how training in virtual reality using visual and auditory feedback on foot placement and the effect on spatiotemporal gait in healthy adults. There were three conditions: (1) real environment, (2) virtual environment with no biofeedback, and (3) virtual environment with biofeedback while walking overground on a pressure-sensitive mat. Immediately post training, participants temporarily adapted an asymmetrical pattern, which persisted in the real environment for several minutes. Spatial (e.g., step length) asymmetries increased, but temporal symmetries did not change. The motor learning principles used to alter symmetry such as feedback along with task specificity can enhance learning.

Motor Learning

Motor learning principles are the foundation for enhancing biomechanical research (Charlton et al., 2021). Feedback is one of the most widely used basic principles in motor learning literature. Visual, auditory, and haptic are common modes of feedback delivery. To assess motor learning with practice and skill acquisition, retention tests are given. However, researchers and clinicians are most interested in whether the skill transfers to other tasks or conditions. Thus, researchers attempt to discover new training and rehabilitation methods.

Basic principles of motor learning and control have been utilized in many different motor skills such as early gait rehabilitation and with motor adaptations to reduce gait asymmetries. Motor learning is used in the formation of a new motor pattern that occurs with long term practice whether it is days, weeks or years (Bastian, 2008). Motor performance and learning is measured in three ways: acquisition, retention, and transfer of skills. Acquisition is the initial practice of a skill; retention is the ability to demonstrate attainment or improvement of skill performance; and transfer is the performance of a similar task (Muratori et al., 2013; Wulf et al., 2010). Motor skill learning is defined as a set of processes associated with practice or experience leading to relatively permanent changes in the capability of skilled movement (Schmidt & Lee, 2018).

Motor adaptation is an error-driven motor learning process that accounts for predicable changes in the environment or ourselves (Malone et al., 2011). This new gait pattern must be unlearned before returning to baseline conditions (Reisman et al., 2005). Adaptation on a split-belt treadmill showed the adaptation was remembered from day one to day two and that the training schedule can affect relearning (Malone et al., 2011). Faster relearning was seen when the adaptation was not washed out between training days. However, when adaptation was washed out, the adaptation was relearned faster when participants adapted and de-adapted in short intervals (Malone et al., 2011).

Fitts' law of the speed-accuracy trade-off is important in motor skill learning (Schmidt et al., 2019). The more accuracy needed (i.e., increasing the difficulty of a task), the slower the task is performed; the faster the task is performed, the less precise the motor performance will be. The difficulty of the task is based on the information processing theory. Information processing theory has multiple stages beginning with detecting and recognizing a stimulus. Then, an identifiable pattern of the stimulus is processed as meaningful. In the response selection, a decision is made on what to do in response to the recognized stimulus (i.e., decision making process with higher cognitive demand). The response programming stage translates the idea decided in the last stage regarding what to do, to make specific and realistic commands of the motor system (Schmidt et al., 2019). This theory is especially important in motor adaptation as responses to perturbations can be anticipated or reactive.

Several factors were shown to enhance the learning of motor skills, which are observational practice, focus of attention, feedback and self-controlled practice (Wulf et al., 2010). Learning results from experience and a great deal of practice. Observational practice combined with physical practice are effective strategies to improve motor skill learning. When participants alternate between observational and physical practice with dyads, participants perform better on the retention tests. It was postulated that in dyad practice, there is enhanced motivation, setting higher goals or a loss of self-consciousness (Wulf et al., 2010). Studies examining focus of attention often report external focus of attention compared to internal focus of attention results in improved performance and learning. External focus of attention seems to increase the rate of the first stages of learning due to movement automaticity (Wulf et al., 2001).

This movement automaticity can be explained by the constrained action hypothesis, which is trying to consciously control one's movements (i.e., internal focus of attention) and constrains the motor system by interfering with automatic motor control processes. In contrast, external focus of attention allows the motor system to more naturally self-organize (Wulf et al., 2001).

Feedback in motor learning provides information about the outcome of the task, knowledge of results or knowledge of performance (Wulf et al., 2010). While knowledge of performance and results are both effective at improving motor skills, knowledge of performance showed better improvement in throwing tasks (Sharma et al., 2016). It was suggested to carefully control the frequency and type of feedback provided. Motivational properties of feedback may influence learning, and that providing positive feedback (i.e., good trials compared to bad/poor trials) is more effective with learning (Wulf et al., 2010). Also, positive comparison regarding norm references (i.e., comparing to other people) improves self-efficacy and increases motivation (Wulf et al., 2010). Also, skill learning can be improved if the participant is given some control over the practice trials (e.g., which trial they would like to receive feedback) (Wulf et al., 2010).

Practice variability can also enhance motor learning skills. Variability of practice is based in Schmidt's schema theory (Schmidt, 2003). The theory states that individuals adapt their movements to efficiently act in a complex environment and that varied practice helps with learning how to interact with the environment (Czyż, 2021; Schmidt, 2003). This theory also indicates that learning is a nonlinear process. The way practice is scheduled can also affect motor learning. Contextual interference states the way the practice is scheduled affects the immediate performance, retention, and transfer differently. If practices were randomly ordered and rapidly changing of multiple motor skills tasks, then that causes high contextual interference. When practice is scheduled or in a blocked order of multiple motor skill tasks, it has low contextual interference. Higher contextual interference can worsen performance compared to low contextual interference, but higher contextual interference facilitates retention (Czyż, 2021; Hall & Magill, 1995; Schmidt et al., 2019: Simon & Bjork, 2001). Therefore, practice variability could be combined with self-controlled practice to enhance motor skill learning.

Motor learning and control principles and theories are important for examining locomotor adaptation and modifications (Charlton et al., 2021; Helm & Reisman, 2015). Several studies investigating locomotor adaption also examined gait asymmetries (Corzani et al., 2019; Malone et al., 2011; Prokop et al., 1995; Reisman et al., 2005, 2007). Thus, motor learning is very important for gait adaptation such as altering gait asymmetries.

Motor Learning in Virtual Reality

Virtual reality has the potential to enhance motor learning principles as virtual reality can be more motivating and enjoyable than traditional training. Multisensory feedback, motivation, level of difficulty, and practice variability are common motor learning principles used in virtual reality training. Virtual reality is suggested to enhance skill acquisition and retention because of the opportunity to employ task specificity, practice repetition and real time feedback (Wulf, 2007). Populations such as older adults, patients with Cerebral Palsy, Parkinson’s disease and poststroke have all shown improvements with training in virtual reality (Cano Porras et al., 2018). Multisensory feedback may enhance motor learning by means of problem solving as well as promoting movement repetition. Janeh and colleagues (2019) used optimizing gait symmetry in Parkinson’s disease as a task specific motor learning strategy along with real time multisensory feedback. A virtual environment with multisensory feedback conditions in addition to making decisions about obstacle negotiation while on a treadmill were used to improve gait, dual task ability and obstacle negotiation in Parkinson's disease patients with greater success than treadmill training alone (Mirelman et al., 2011).

The goal of rehabilitation interventions is to improve motor skills through repetition of relearning or learning new motor skills so that these skills can transfer to activities of daily living. Transfer of training is another motor learning principle that can be examined with virtual reality training including obstacle avoidance, postural tasks, and gait (Levac et al., 2019; LoJacono et al., 2018). Mendes and colleagues (2012) examined learning, retention and transfer after virtual reality training using Nintendo Wii Fit in healthy elderly adults and Parkinson's disease patients. Patients with Parkinson's disease had performance deficits due to task difficulties in the game compared to healthy elderly adults; however, the Parkinson's disease patients were able to transfer the reaching task ability to a similar untrained task (Mendes et al., 2012). Whether virtual reality gait training outcomes are retained and can transfer to the real world remains limited.

Current Gaps in the Literature with Regards to this Dissertation

Many gaps in the literature still exist in regard to gait asymmetry and using a visual asymmetrical cue to alter gait symmetry in healthy adults. Current methods to alter gait asymmetries rely heavily on split-belt treadmill training. Gait training using visual cues that are projected on a screen or in immersive virtual reality have been shown to produce greater improvements in gait asymmetries than traditional treadmill training alone. However, it is unclear the extent to which gait asymmetries can be systematically altered using an asymmetric visual cue, which represents a more cost-effective strategy relative to split-belt treadmill training or immersive virtual reality. Despite empirical evidence supporting the ability for gait symmetry to be altered in healthy and clinical populations, it remains unknown whether the changes in gait symmetry will be retained once the asymmetric cue is removed and if these asymmetries will transfer to overground walking. Investigating whether using a visual asymmetric cue can alter gait symmetry in healthy adults is the first step in determining if this methodology is plausible for future research with clinical populations.

CHAPTER III: OUTLINE OF PROCEDURES

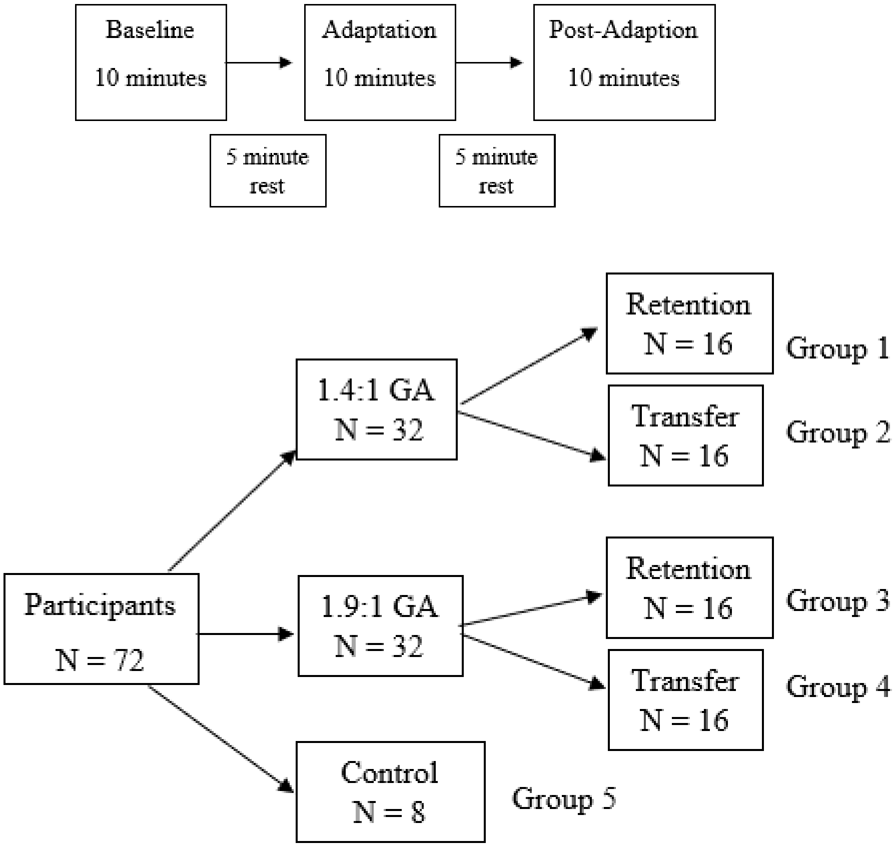
Participants

We recruited 72 participants (90 intended - 72 collected) from the Greensboro Triad area that were 18-50 years old due to motor changes that occur after the age of 50 (Coats et al., 2014). Participants were screened for eligibility via email or in-person. Individuals were excluded based on the following criteria: (1) inability to continuously walk for 10-minutes, (2) any musculoskeletal injury or impairments in the last year, (3) limb length discrepancies greater than 2 cm, (4) any neurological, cognitive, or musculoskeletal disorder or disease, (5) any visual impairments or non-corrected vision, and (6) a Body Mass Index (BMI) of >30 to exclude individuals who are obese, which can affect gait (Silva et al., 2018). Participants were quasi-randomized into a control group or one gait asymmetry (GA) ratio group (i.e., 1.4-1 or 1.9-1), and either the retention or transfer group for a total of five groups. The retention groups remained on the treadmill after the visual cue was removed, and the transfer groups stepped off the treadmill and walked overground.

Experimental Design

The institutional review board at the University of North Carolina Greensboro (UNCG) approved the study procedures prior to data collection. All data collection occurred at UNCG's main campus in the Virtual Environment for Assessment and Rehabilitation (VEAR) Laboratory and Coleman Gym (transfer only groups). After obtaining written informed consent, participants were examined for limb length discrepancies greater than 2 cm, as it is associated with gait asymmetries, (Kaufman et al., 1996; Khamis & Carmeli, 2017) through the direct method of measuring the anterior superior iliac spine to the medial malleolus while lying supine (Woerman & Binder-Macleod, 1984). Participants completed a basic health history and demographic questionnaire, a limb dominance questionnaire via the Waterloo Footedness Questionnaire-Revised (WFQ-R), and a physical activity questionnaire via the International Physical Activity Questionnaire (IPAQ)- short form. Participants were quasi-randomized into the smaller 1.4-1 or larger 1.9-1 gait asymmetry ratio group and into either the retention or transfer group as well as a control group for a total of five groups (**Figure 1**).

Figure 1. Experimental Design



Procedures/Instrumentation

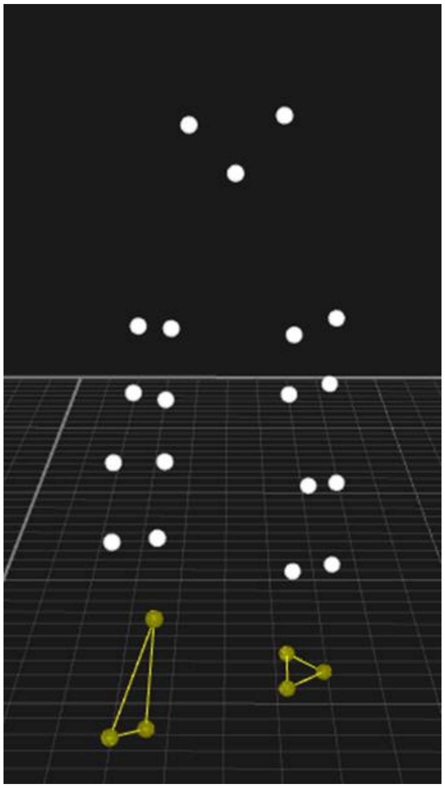
Participants were fitted with seven inertial wearable sensors (APDM Inc., Portland, OR, USA); sensors were placed on the following locations: the low back at the base of the spine, lateral aspect of the thighs at midline, shin above the widest part of the gastrocnemius, and on top and centered of each foot. Data was sampled at 128Hz based on the equipment’s capabilities.

Spatiotemporal gait measures will be obtained using APDM’s Mobility Lab (Washabaugh et al., 2017). Participants’ preferred walking speed was determined on the ActiveStep treadmill (Simbex Active Step, Lebanon, NH). The preferred walking speed was determined by increasing the treadmill in increments of 0.05 mph from zero until the participant indicated that it was their preferred speed. Then, the treadmill was further increased before decreasing by 0.05 mph until the participant indicated it was their preferred speed (Dingwell & Marin, 2006). The preferred walking speed was the average of the two speeds. Participants then began baseline walking followed by adaptation with the visual cue and then post adaptation with five minute seated rest periods between each condition (**Figure 1**). Participants completed the NASA Task Load Index (NASA-TLX) to assess perceived workload at the end of each walking trial: baseline, adaptation, and post adaptation as this has not been accounted for in previous gait adaptation training studies.

Gait Adaptation

Participants walked for 10 minutes on the treadmill for baseline, followed by 10 minutes of walking adaptation to a visual cue and then 10 minutes of retention or overground transfer with five minutes of rest in between conditions (**Figure 1**). The visual cue is derived from asymmetric walking motion capture data of healthy adults on a split-belt treadmill that shows the pelvis and lower extremities (**Figure 2**). Two ratios of gait asymmetry were chosen for the visual cue: (1) a smaller ratio of 1.4-1 that has slight noticeable differences in limb behavior and (2) a larger ratio of 2, which is the ratio commonly used in locomotor adaptation literature (Malone & Bastian, 2014; Reisman et al., 2007). The visual cue was projected onto a large screen in front of the participant and showed the asymmetric walking visual cue from the back as if following a leader. Participants will be asked to “Mimic the walking cue as closely as you can to the best of your ability." At the end of the post adaptation session, participants will be provided a questionnaire that asks what part of the visual cue they focused on, and how even they felt walking with and without the visual cue via a Visual Analog Scale (Appendix A).

Figure 2. Freeze-frame of Visual Cue.



Statistical Analyses

R version 4.2.2 was used to create a custom script to calculate the gait asymmetries from the wearable sensors (APDM Inc., Portland, OR, USA) using the Symmetry Index equation (**Figure 3**). The Symmetry Index is the most sensitive method to calculate spatiotemporal gait symmetry in healthy adults (Błażkiewicz et al., 2014). The *p* value was set at 0.05 a priori. Post hoc analyses were performed as needed. All data analyses were performed using R (R, Version 4.2.3; R Foundation for Statistical Computing, Vienna, Austria). All outcome variables were run through an R script to calculate gait asymmetries via the Symmetry Index Equation (**Figure 3**), and gait asymmetries are considered present if the value is not zero (Błażkiewicz et al., 2014). After visually inspecting the data, some participants exhibited minimal changes while others exhibited more obvious changes from baseline to adaptation. Therefore, participants were further divided into non-responder (i.e., ≤ 1% difference in all of the outcome variables) or responders (> 1% difference in at least one outcome variable) (Appendix C). To address the exponential decay effect that can occur during retention or transfer of a task, all conditions: baseline, adaptation and post adaptation (i.e., retention and transfer) data were sectioned into 1-minute windows, for a total of 10-minutes for each condition.

Figure 3. Symmetry Index Equation.

Symmetry Index (SI): $SI = \frac{x_L - x_R}{0.5*(x_L + x_R)} * 100$

Aim 1: Examine the extent to which healthy adults could synchronize to an asymmetric visual cue during a 10-minute treadmill walking session with asymmetric gait ratios: 1.4-1 (small asymmetry) and 1.9-1 (large asymmetry).

- Hypothesis 1: Participants would exhibit an asymmetric walking pattern when synchronizing to the 1.4-1 ratio and 1.9-1 ratio. Participants in the 1.9-1 ratio group would exhibit greater stride length asymmetry, step duration asymmetry, and single limb support asymmetry compared to the 1.4-1 ratio group.

One-way ANOVAs were used to compare group demographics (**Table 1**). The Shapiro-Wilks test (R package "rstatix") was utilized to assess the distribution of each outcome variable (SLS SI%, step duration SI %, and stride length SI%), which indicated the variables were non-normally distributed. Therefore, non-parametric Wilcoxon Signed Rank and Mann Whitney U tests (R package "stats") were performed to compare gait asymmetry indices (SLS SI%, step duration SI %, and stride length SI%) at baseline to adaptation and between groups. Only the

10th minute of each walking condition was used in the analyses. To assess the strength of the association between groups and gait asymmetry indices, we calculated the Wilcoxon Q effect size (R package “rstatix”). As the sample size is small due to the further division of groups based on if participants were categorized as a responder or not in addition to the data not having a normal distribution, the data were bootstrapped (5000 samples) with a bias correction for confidence intervals to calculate effect sizes. The values for the Wilcoxon Q effect size are interpreted as follows: $r < 0.30$ = small effect, $r = 0.30\text{-}0.49$ = medium effect, and $r \geq 0.50$ = large effect (Wilcox, 2019). For all analyses, alpha level was set a priori at 0.05.

Aim 2: Explored if the asymmetric walking pattern was retained once the visual cue was removed during a 10-minute treadmill walking session after the initial training session.

- Hypothesis 2a: Participants would retain stride length asymmetry, step duration asymmetry, and single limb support asymmetry for 10 minutes.
- Hypothesis 2b: Participants in the 1.9-1 ratio group would exhibit greater gait asymmetry than the 1.4-1 ratio group during the retention period.

Aim 3: Examined transfer of the asymmetric walking pattern to overground walking after the treadmill training session in a 10-minute period after the initial training session.

- Hypothesis 3a: Participants would exhibit stride length asymmetry, step duration asymmetry, and single limb support asymmetry for 10 minutes during overground walking.
- Hypothesis 3b: Participants in the 1.9-1 ratio group would exhibit greater gait asymmetry than the 1.4-1 ratio group during overground walking.

One-way ANOVAs were used to compare group demographics (**Table 2**). Non-parametric Wilcoxon Signed Rank and Mann Whitney U tests (R package “stats”) were performed to compare gait asymmetry indices (SLS SI%, step duration SI %, and stride length SI%) at adaptation and post adaptation (i.e., retention and transfer) as well as between asymmetry groups. Only the 10th minute was used in the analyses. For all analyses, alpha level was set a priori at 0.05.

CHAPTER IV: MIMICKING ASYMMETRIC VISUAL CUES ALTERS GAIT SYMMETRY IN HEALTHY ADULTS

Introduction

Neurological populations such as people with a history of stroke or Parkinson’s disease commonly exhibit gait impairments such as gait asymmetries. People with gait asymmetries reduce the amount of weight bearing on the paretic or injured limb, which can lead to further muscular imbalances and loss of bone mineral density (Jørgensen et al., 2000a). Therefore, a primary goal of gait rehabilitation is to improve weight bearing on the paretic or affected limb (Patterson et al., 2008). In clinical and elderly populations, cognitive demand can impact the magnitude of gait asymmetries as dual tasks show increased gait asymmetries (Yogev et al., 2007). Gait asymmetries are also associated with decreased walking speed and balance control, and increased metabolic cost and fall risk (Awad et al., 2015; Lewek et al., 2014; Patterson et al., 2008; Wei et al., 2017). Falls can lead to reduced quality of life, critical injuries and loss of independence, which is of great concern for clinical and aging populations who exhibit gait asymmetries (Alexander et al., 1992; Axer et al., 2010; Contreras & Grandas, 2012; Mahlknecht et al., 2013; Malone & Bastian, 2014; Sterling et al., 2001; Wagner et al., 2009). Thus, gait asymmetries are important to assess in clinical and aging populations and are a better indicator of functional recovery than velocity due to the weight bearing aspect (Brandstater et al., 1983; Patterson et al., 2008).

Methods to reduce gait asymmetries and fall risk have heavily relied on split-belt treadmill training to alter gait in clinical populations (Nanhoe-Mahabier et al., 2013; Reisman et al., 2007, 2013; Roemmich, Nocera, et al., 2014). The split-belt treadmill training can be used as an error-based motor learning strategy during adaptation to reduce gait asymmetries when the belts are once again tied at the same speed. Split-belt treadmill training has shown success in altering gait asymmetries (e.g., step length, stride length and double support time asymmetries) during adaptation conditions in which the belts are split in young healthy adults and in clinical populations (Reisman et al., 2005, 2007; Roemmich, Nocera, et al., 2014). Aftereffects (i.e., changes to asymmetry remained after the belts went from split to tied) especially in step length in young healthy adults and clinical populations as well as double support time (Reisman et al., 2007; Roemmich, Nocera, et al., 2014). Although, some gait metrics like stance time are more difficult to alter (Lewek et al., 2014; Reisman et al., 2007, 2013). Multiple sessions of split-belt training can improve step length asymmetries and the improvements may last from one to several months post training (Lewek et al., 2018; Reisman et al., 2013). Thus, indicating split-belt treadmill training in clinical populations can reduce certain gait asymmetries. However, split-belt treadmills are expensive and mainly conducive to lab-based training only. Therefore, it's important to explore alternative cost-effective options to alter gait that has greater clinical applicability.

Gait can be altered through a variety of ways such as using external cuing through visual cues. Visual cuing can be done via projections on a screen or in immersive virtual reality, which have produced greater improvements in gait and gait asymmetries than traditional treadmill training alone (Cano Porras et al., 2018; Janeh et al., 2019; Keshner & Lamontagne, 2021). Besides visual cuing as an external cue to alter movement, synchronization of movement can occur with external cues such as another human, avatars, and auditory metronomes (Liu et al., 2020; L. A. Meerhoff et al., 2019; Rhea, Kiefer, D'Andrea, et al., 2014; Soczawa-Stronczyk & Bocian, 2020). Synchronization between two individuals can be intentional (i.e., cued) or spontaneous, and intentional synchronization can produce greater synchrony than spontaneous synchronization. Intentionally synchronizing to a human and an avatar in an immersive environment produces similar results suggesting both methods are effective (Soczawa-Stronczyk & Bocian, 2020). Thus, visual cueing combined with an additional external cue such as intentional instructions to synchronize to a human or avatar may influence gait changes such as gait asymmetry. However, the ability to synchronize with an asymmetric walking pattern that simulates a split-belt treadmill to alter gait symmetry is unknown.

Therefore, the purpose of this study was to examine the extent to which healthy adults could synchronize to an asymmetric visual cue during a 10-minute treadmill walking session with a small or large gait asymmetry. This was part of a larger study that also examined retention and transfer of gait asymmetries after the visual cue was removed; however, this manuscript specifically focused on adaptation due to the novel methodological approach. We hypothesized gait asymmetries would increase from baseline to adaptation and the large asymmetry cue would induce greater gait asymmetries than the small asymmetry cue.

Methods

Participants

A total of 72 participants (49 females and 23 males) were recruited for this study and were quasi randomized into three groups: Small Gait Asymmetry (*n* = 32), Large Gait Asymmetry (*n* = 32), and Control (*n* = 8). Participants were between the ages of 18-50 years old, BMI < 30, had normal or corrected to normal vision, and the ability to walk continuously for at least 10 minutes. All participants reported no lower extremity injuries in the last 12 months, and no musculoskeletal, cognitive or neurological conditions.

Experimental Procedures

All data collection occurred in the Virtual Environment for Assessment and Rehabilitation (VEAR) laboratory at the University of North Carolina Greensboro. Prior to data collection, the study's procedures were approved by the university's institutional review board. Participants completed the informed consent on Qualtrics and then were screened for limb length discrepancies via the direct method (i.e., measurement between the bony landmarks of the anterior superior iliac spine and the medial malleolus with a tape measure) to ensure any discrepancies were less than 2 cm, as greater than 2 cm is related to gait asymmetries (Kaufman et al., 1996; Khamis & Carmeli, 2017). Participants completed a demographics/health history questionnaire, Footedness questionnaire, and the International Physical Activity Questionnaire short form (IPAQ-SF) via Qualtrics. Next, participants stepped onto the treadmill (Simbex Active Step, Lebanon, NH) to determine their preferred walking speed (Dingwell & Marin, 2006). Then, a total of seven Opal wearable sensors (APDM Inc, Portland, OR) were placed on the following locations: top and center of feet, shins with straps above the widest part of the gastrocnemius muscles, lower lateral side of thigh at midline, and the low back at the base of the spine. Next, participants walked for two conditions at their preferred walking speed. Condition 1 was walking for 10-minutes (baseline), and condition 2 participants walked with the visual cue (adaptation). Participants were instructed to synchronize their gait to the visual cue via the following instructions "mimic the walking cue as closely as you can to the best of your ability." A five-minute seated rest period was provided between walking conditions to reduce the possibility of fatigue.

The Small Gait Asymmetry group received the visual cue exhibiting a small gait asymmetry (1.4-1 ratio) presented on the projection screen in front of that treadmill, while the

Large Asymmetry Group received the visual cue with a large gait asymmetry (1.9-1 ratio). The asymmetrical visual cue was created using data of healthy adults walking on a split-belt treadmill to create an asymmetrical walking pattern. To incorporate simulating a clinically relevant gait asymmetry, we used two different ratios of gait asymmetry for the asymmetrically walking visual cue based on velocity of the treadmill belts. One visual cue has a small gait asymmetry with a ratio of 1.4-1 (i.e., the left side is moving about 40% faster than the right) and a large gait asymmetry ratio of 1.9-1 (i.e., the left side is moving about 90% faster than the right side) for an average treadmill speed of both belts at 1.24 m/s. The small asymmetrical ratio is slightly under threshold of what is clinically detected based on observation alone (Patterson et al., 2008), and the large asymmetrical ratio is close to a 2-1 ratio, which is commonly used in split-belt treadmill training to reduce gait asymmetries (Reisman et al., 2007, 2009, 2013).

Statistical Analyses

All data analyses were performed using R (R, Version 4.2.3; R Foundation for Statistical Computing, Vienna, Austria). One-way ANOVAs were used to compare group demographics (**Table 1**). All outcome variables were run through an R script to calculate gait asymmetries via the Symmetry Index Equation (**Figure 3**), and gait asymmetries are considered present if the value is not zero (Błażkiewicz et al., 2014). After visually inspecting the data, some participants exhibited minimal changes while others exhibited more obvious changes from baseline to adaptation. Therefore, participants were further divided into non-responder (i.e., ≤ 1% difference in all of the outcome variables) or responders (> 1% difference in at least one outcome variable). The Shapiro-Wilks test (R package “rstatix”) was utilized to assess the distribution of each outcome variable (SLS SI%, step duration SI %, and stride length SI%), which indicated the variables were non-normally distributed. Therefore, non-parametric Wilcoxon Signed Rank and

Mann Whitney U tests (R package “stats”) were performed to compare gait asymmetry indices (SLS SI%, step duration SI %, and stride length SI%) at baseline to adaptation and between groups. Only the 10th minute of each walking condition was used in the analyses. To assess the strength of the association between groups and gait asymmetry indices, we calculated the Wilcoxon Q effect size (R package “rstatix”). As the sample size is small due to the further division of groups based on if participants were categorized as a responder or not in addition to the data not having a normal distribution, the data were bootstrapped (5000 samples) with a bias correction for confidence intervals to calculate effect sizes. The values for the Wilcoxon Q effect size are interpreted as follows: $r < 0.30$ = small effect, $r = 0.30$-0.49 = medium effect, and $r \geq 0.50$ = large effect (Wilcox, 2019). For all analyses, alpha level was set a priori at 0.05.

Results

One-way ANOVA revealed a significant difference between preferred walking speed between the groups ($p = 0.011$) (**Table 1**). A post hoc test with Bonferroni correction showed the Control group had a faster preferred walking speed than the small and large asymmetry group responders ($p = 0.0075$ and $p = 0.0014$ respectively). No other statistically significant differences for the remaining demographic variables were observed. The Wilcoxon Signed Rank tests revealed in the small asymmetry group responders from baseline to adaptation that the single limb support SI % ($V = 34$, $p = 0.003$) and step duration SI % ($V = 50$, $p = 0.02$) increased, but stride length SI % was not significantly different ($V = 88$, $p = 0.273$) (**Figure 4**). Also, a large effect size was observed with the single limb support SI % ($r = 0.59$, CI [0.13, 0.8]), a medium effect size for step duration SI % ($r = 0.46$, CI [0.04, 0.74]), and a small effect size for stride length SI % ($r = 0.14$, CI [0, 0.43]). The Wilcoxon Signed Rank tests revealed significant differences in the large asymmetry group responder from baseline to adaptation as the single limb support SI % (V = 43, $p = 0.003$), step duration SI % (V = 41, $p = 0.002$) and stride length SI % (V = 33, $p = 0.0007$) increased in the adaptation condition. Large effect sizes were observed for SLS SI % ($r = 0.58$, CI [0.16, 0.79]), step duration SI % ($r = 0.59$, CI [0.11, 0.81]), and stride length SI % ($r = 0.65$, CI [0.29, 0.83]).

The Wilcoxon Signed Rank tests revealed in the small asymmetry group non-responders from baseline to adaptation no statistically significant differences in single limb support SI % (V = 48, $p = 0.765$), step duration SI % (V = 36, $p = 0.425$), and stride length SI % (V = 39, $p = 0.515$) (**Figure 5**). Also, small effect sizes were observed with the single limb support SI % ($r = 0.20$, CI [0, 0.59]), and step duration SI % ($r = 0.07$, CI [0, 0.18]). The effect is too small for stride length SI % to calculate confidence intervals. The Wilcoxon Signed Rank tests revealed no significant differences in the large asymmetry group non-responders from baseline to adaptation for single limb support SI % (V = 17, $p = 0.161$), step duration SI % (V = 28, $p = 0.539$) and stride length SI % (V = 18, $p = 0.188$). However, moderate effect sizes were observed for SLS SI % ($r = 0.34$, CI [0.02, 0.79]) and stride length SI % ($r = 0.31$, CI [0.02, 0.76]). The effect is too small for step duration SI % to calculate confidence intervals. The Wilcoxon Rank sum tests (i.e., Mann Whitney U test) to compare the small and large asymmetry group responders on the gait asymmetry metrics revealed no statistical differences between groups on SLS SI % (W = 193, $p = 0.254$, CI[$-\infty$, 0.480]), step duration SI % (W = 193, $p = 0.122$, CI[$-\infty$, 0.219]), and stride length SI % (W = 177, $p = 0.144$, CI[$-\infty$, 0.230])] (**Figure 6**). Based on our criteria for responder, three control participants were categorized as responders; however, when comparing the control responders to the non-responders, no significant differences were shown. Thus, the control group was recombined to include responders and non-responders. The control group did not significantly change from baseline to adaptation in single limb support SI%, step duration SI% or stride length SI% (**Figure 7**).

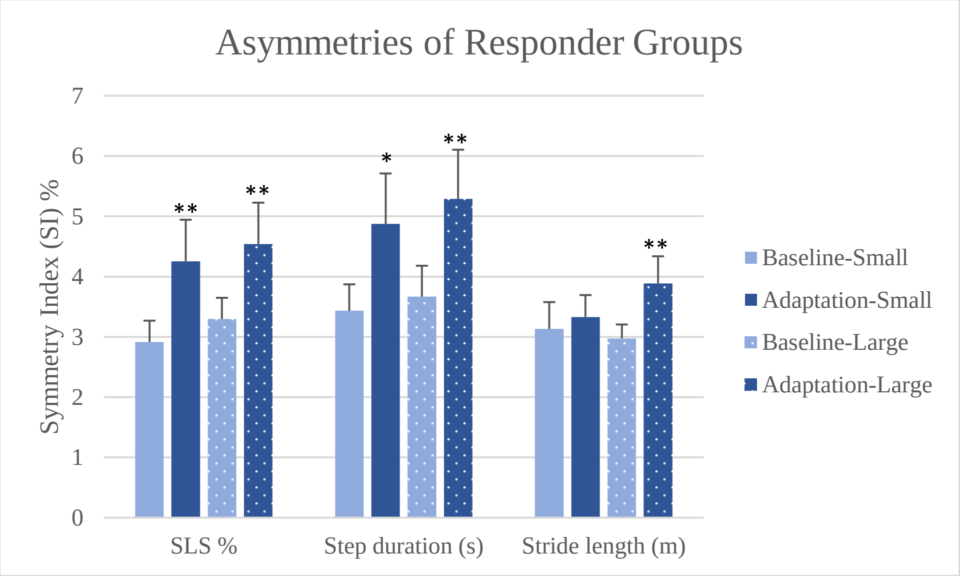
Table 1. Participant Demographics - means (SE)

Variables	Small Res (n = 20)	Small Non-R (n = 12)	Large Res (n = 22)	Large Non-R (n = 10)	Control (n = 8)	p
Age (years)	24.09 (6.29)	22.62 (7.30)	23.57 (4.33)	23.93 (6.98)	26.16 (2.37)	0.520
Height (cm)	168.29 (10.50)	166.32 (8.93)	167.97 (8.90)	169.20 (5.79)	168.20 (3.77)	0.822
Weight (kg)	70.22 (15.45)	68.00 (17.40)	71.07 (16.68)	75.89 (9.98)	69.97 (2.79)	0.564
Preferred Walking Speed (m/s)	0.88 (0.16)	0.93 (0.18)	0.84 (0.16)	0.96 (0.15)	1.14 (0.09)	0.011*
Left leg length (cm)	88.40 (6.67)	88.31 (5.22)	87.69 (5.96)	89.32 (3.35)	88.60 (2.10)	0.860
Right leg length (cm)	88.37 (6.91)	88.75 (5.38)	87.72 (6.26)	89.12 (3.31)	88.68 (2.13)	0.906
Leg length difference (cm)	0.51 (0.30)	0.56 (0.44)	0.39 (0.30)	0.50 (0.28)	0.30 (0.07)	0.128

Note: Small Res= Small Asymmetry Group Responders, Small Non-R= Small Asymmetry Group Non-Responders, Large Res= Large Asymmetry Group Responders, Large Non-R= Large Asymmetry Group Non-Responders

* Indicates $p < 0.05$

Figure 4. Comparison of Baseline to Adaptation in the Responder Groups – means (SE)

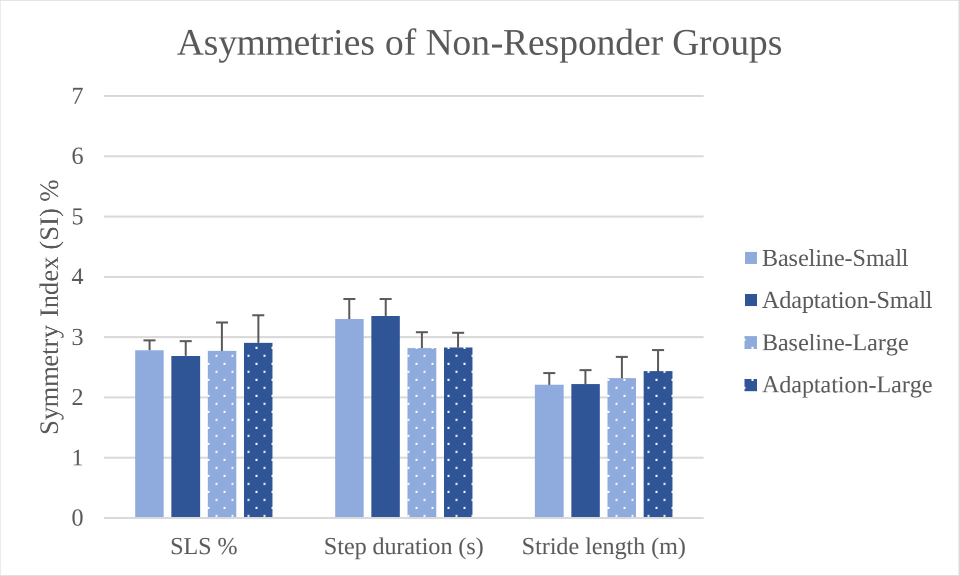


Note. SLS % SI % = Single limb support %.

* Indicates $p < 0.05$ from baseline to adaptation

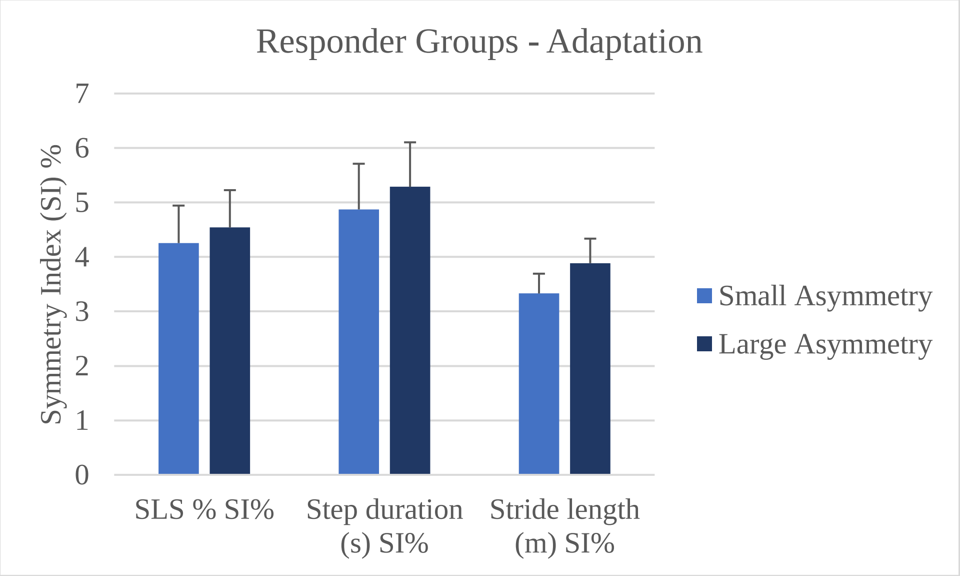
** Indicates $p < 0.01$ from baseline to adaptation

Figure 5. Comparison of Baseline to Adaptation in the Non-Responder Groups – means (SE)



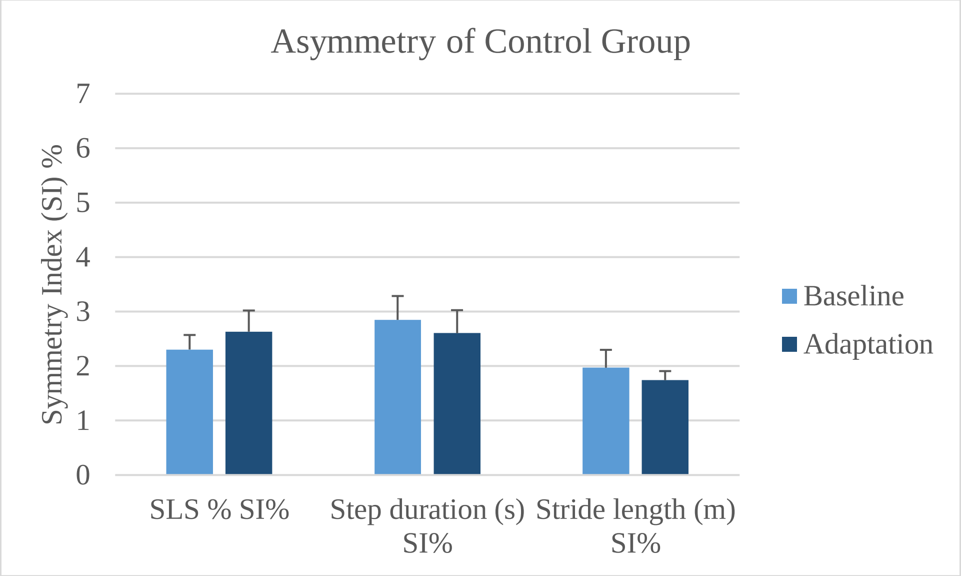
Note: SLS % SI % = Single limb support %

Figure 6. Comparison of Responder Groups - means (SE)



Note: SLS % SI % = Single limb support %

Figure 7. Comparison of Baseline to Adaptation in Control group - means (SE)



Note: SLS % SI % = Single limb support %

Discussion

The aim of this study was to examine the extent to which healthy adults can synchronize to an asymmetric visual cue during a 10-minute treadmill walking session with a small or large gait asymmetry. This study specifically examined the 10th minute of baseline and adaptation. We hypothesized that gait asymmetries would increase from baseline to adaptation. Our hypothesis was mainly supported by the responder groups. In the small and large asymmetry group-responders, single limb support SI% and step duration SI% both increased during adaptation indicating that mimicking an asymmetric cue can alter gait symmetry in healthy adults. The increases in single limb support asymmetry observed in the responder groups are indirectly supported by the literature as changes were previously shown with double support asymmetry with split-belt treadmill training (Reisman et al., 2007; Roemmich, Nocera, et al., 2014). The changes in single limb support % and step duration asymmetry suggest temporal measures may be altered with an asymmetrical visual cue in healthy adults similar to what Roemmich and colleagues (2014) reported in their healthy young adult group. However, temporal changes may be harder to alter in clinical or aging populations (Lewek et al., 2014, 2018; Roemmich, Nocera, et al., 2014).

Interestingly, the stride length SI% did not increase for the responders in the small asymmetry responder group but did increase in the large asymmetry responder group. The lack of changes to symmetry in the small asymmetry group may be due to the fact the small asymmetry visual cue was subthreshold of what is clinically observable as having an asymmetric gait. The small asymmetry visual was a ratio of 1.4-1, while clinical observable asymmetry is a 1.5-1 ratio according to Patterson et al. (2008). The asymmetrical visual cue ratio was based on speed, which may suggest participants were primarily focused with the timing of synchronizing to the visual cue rather than the spatial aspect such as in the stride length. The large asymmetry ratio is similar to what is seen in the split-belt treadmill literature (Prokop et al., 1995; Reisman et al., 2005), so this may be why changes in stride length were seen only in the large asymmetry group and not the small asymmetry group.

In addition, we hypothesized participants in the large asymmetry group would exhibit greater gait asymmetries than the small asymmetry group. Our hypothesis was not supported by our results as no differences between the small and large asymmetry groups were found, even though we examined the responder groups. The findings were surprising as the large asymmetrical visual cue had an obvious asymmetrical gait pattern, while the small asymmetrical visual cue was not as easily noticeable. In contrast to our findings, Reisman and colleagues (2005) reported greater gait asymmetries for larger speed ratios of the belts. While we didn’t see differences when comparing the small and large responder groups, the magnitude of effect sizes varied between the small and large asymmetry groups. The effect size of the single limb support SI% was large effect size for the small and large asymmetry responder groups. Step duration

SI% was a moderate effect for the small asymmetry responder group and large for the large asymmetry responder group. The stride length SI% was small for the small asymmetry responder group, and large for the large asymmetry responder group. The magnitude of the effect size indicates that the large asymmetrical visual cue has a greater impact on adaptation than the small asymmetrical visual cue. No significant differences were observed in the non-responder groups on gait asymmetries; although, the small asymmetry non-responder group have small effect sizes, while the large asymmetry-non responder group showed medium effect sizes.

Interestingly, 20 out of the 64 experimental group participants did not respond to the visual cue. Greater changes in gait are seen in early adaptation with split-belt treadmill training, so the lack of response may be that participants adapted early to the cue since this study only examined the 10th minute of adaptation (Bruijn et al., 2012; Reisman et al., 2005; Roemmich, Nocera, et al., 2014) However, attention during the adaptation condition may play a role in whether a participant adapted to the visual cue or not. While in the health history questionnaire asked and excluded anyone with a neurological or cognitive disease or disorder, attentional deficit disorders may not have been considered by participants. Attentional deficit disorders are very common and may not be thought of as a neurological disorder by the study's participants as research is limited on how attentional disorders in adults can affect how they walk. However, research in children with attentional disorders show greater stride to stride variability during walking, but reduced variability with dual tasks (Leitner et al., 2007).

Motor learning principles such as rate of adaptation should also be considered in future research as this study only focused on the 10th minute of adaptation. The rate of adaptation can tell us more information of the learning process when adapting to a novel gait task. The literature involving adaptation with split-belt treadmill shows immediate adaptation (i.e., the greatest differences) compared to the end of adaptation as most healthy participants move back toward symmetry (Bruijn et al., 2012; Reisman et al., 2005). Thus, early adaptation should be compared to late adaptation to examine whether gait asymmetries were greater during the early adaptation condition. Also, Fitts' law should be considered as well due to the fact this study used novel methods and speed may be an important component influencing accuracy of mimicking the visual cue that could contribute to difficulty of the task (Schmidt et al., 2019). Bootsma and colleagues (2018) postulated that the magnitude of motor skill learning on task difficulty may be mediated by perceived mental workload. Most gait adaptation studies have not asked participants how difficult they felt the task was, which may be impacting the accuracy or optimization of adaptation. The study that did examine perceived exertion reported that participants were divided into responders and non-responders, and responders indicated a greater perceived exertion with overground walking than the non-responders on the first day of training (Reisman et al., 2013).

A few limitations exist within our study. Sample size was small once groups were further divided into responders and non-responders. We only examined the 10th minute of each condition, so early adaptation was not examined. Our participants were younger healthy adults, so our study lacks generalizability to a clinical population.

Overall, this study indicates that an asymmetric visual cue can alter gait symmetry in healthy adults. Future research should investigate why some people did not respond to the visual cue and examine if difficulty or mental workload was a factor in the lack of a response for some participants. In addition, earlier time points within the adaptation phase should be examined. Also, future research should examine replicate the study using the asymmetrical visual cue with a clinical population.

CHAPTER V: RETENTION AND TRANSFER OF SPATIOTEMPORAL GAIT ASYMMETRIES AFTER WALKING WITH ASYMMETRIC VISUAL CUES

Introduction

Adapting to the environment when walking is an essential component of a healthy system in humans (Lipsitz, 2002). During walking, limb movements must be sufficiently flexible to maintain stability when navigating the natural and built environment such as changing speed or direction to avoid colliding with another person or stepping over a curb (Chen et al., 1994; Reisman et al., 2005). Aging, disease or injury can impact a person’s ability to adapt (Bruijn et al., 2012; Dietz et al., 1995). Therefore, the ability to adapt or relearn a motor skill, such as in gait adaptation training, is an important component of rehabilitation.

Early research on gait adaption showed healthy adults can quickly adapt to split-belt treadmill training and after a short interruption can adapt even faster along with alterations in gait remaining once the belts were once again at the same speed (Prokop et al., 1995). Similarly, Reisman et al. (2005) reported healthy adults can adapt to split-belt treadmill training, but the participants quickly returned back to baseline measures. The difference in findings were postulated to be due to stopping the treadmill between conditions to change belt speeds, whereas Prokop (1995) changed belt speeds while participants continued walking. Nonetheless, the interlimb changes observed that altered gait symmetry in healthy adults using a split-belt treadmill gave way to split-belt treadmill training in clinical populations with gait impairments along with other methods to alter gait.

Many gait adaptation studies that are designed to directly alter gait asymmetries though split-belt treadmill training have focused on aftereffects. Aftereffects are when changes to gait are seen during post adaptation (i.e., when belts move at the same speed) as it showed learning was taking place, so aftereffects are commonly discussed as retaining an adapted gait pattern (Reisman et al., 2005). People with a history of stroke remained able to adapt to different split-belt conditions similar to healthy adults and produced aftereffects, resulting in an improved gait pattern (i.e., reduced gait asymmetries) of step length and double support time (Reisman et al., 2007). Similar to the findings of the gait adaptation studies using a split-belt treadmill with participants with a history of stroke, people with Parkinson's disease exhibit improvements in gait asymmetry after training (Roemmich, Hack, et al., 2014).

Gait adaptation training may be enhanced with the use of external cues such as visual cuing. Gait adaptation training using visual cuing in virtual reality altered gait dynamics in healthy adults, and the changes in gait were retained for 15 minutes (Rhea, Kiefer, Wittstein, et al., 2014). Combining visual cue with adaption training with a split-belt treadmill showed improvements in reducing gait asymmetry immediately after adaptation training (Levin et al., 2017; Lewek et al., 2012).

Retention in gait adaptation training is an important aspect of rehabilitation; however, transfer is a critical component that needs to be assessed for success with long term rehabilitation (Reisman et al., 2009). However, few studies have examined whether gait adaptation training can transfer the adopted gait pattern to overground walking. Reisman and colleagues (2009) examined whether gait asymmetry changes can be exhibited when transferring to overground walking in people with a history of stroke and reported aftereffects were seen with reduced step length and double limb support asymmetries after split-belt treadmill training. Though, the few that examined repeated training using a split-belt treadmill, reported reduced asymmetries with overground walking at one to nearly three months after gait adaptation training (Betschart et al., 2018; Lewek et al., 2018; Reisman et al., 2013). Therefore, not only is retention important, but is it is essential to also examine transfer after gait adaptation training to optimize motor learning strategies and ensure success for long term rehabilitation, which is missing from much of the gait adaptation literature to alter gait asymmetries.

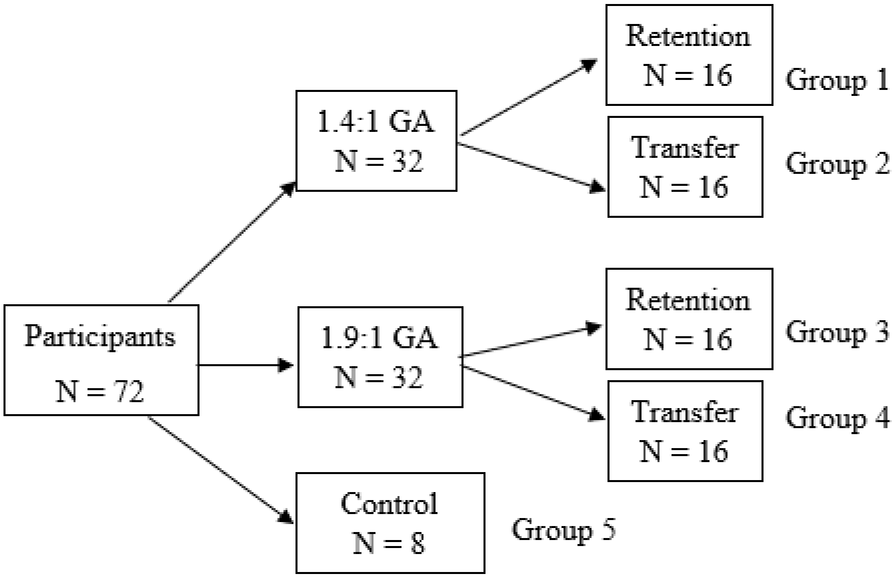
The purpose of this study was to explore if the asymmetric walking pattern was retained once the visual cue was removed; and to examine transfer of the asymmetric walking pattern to overground walking after the treadmill training session. We hypothesized participants would retain the gait asymmetries after the visual cue was removed (Aim 1), and that gait asymmetries would persist in overground walking (Aim 2). Also, we hypothesized that the larger gait asymmetry groups would exhibit greater asymmetries in retention and transfer than the smaller gait asymmetry groups.

Methods

Participants

A total of 72 participants (49 females and 23 males) were recruited for this study and were quasi randomized into the large gait asymmetry group, the small gait asymmetry group, or control group. The large and small gait asymmetry groups were further divided into retention (i.e., walking on the treadmill) or transfer (i.e., walking on ground level), resulting in a total of four experimental groups and a control group (**Figure 8**). Participants were between the ages of 18-50 years old, BMI < 30, had normal or corrected to normal vision, and the ability to walk continuously for at least 10 minutes. All participants reported no lower extremity injuries in the last 12 months, and no musculoskeletal, cognitive, or neurological conditions.

Figure 8. Experimental Design of All Groups.



Experimental Procedures

All data collection occurred in the Virtual Environment for Assessment and Rehabilitation (VEAR) laboratory and Coleman Gym at the University of North Carolina Greensboro. Prior to data collection, the study's procedures were approved by the university's institutional review board. Participants completed the informed consent on Qualtrics and then were screened for limb length discrepancies via the direct method (i.e., measurement between the bony landmarks of the anterior superior iliac spine and the medial malleolus with a tape measure) to ensure any discrepancies were less than 2 cm, as greater than 2 cm is related to gait asymmetries (Kaufman et al., 1996; Khamis & Carmeli, 2017). Participants completed a demographics/health history questionnaire, Footedness questionnaire, and the International Physical Activity Questionnaire short form (IPAQ-SF) via Qualtrics. Next, participants stepped onto the treadmill (Simbex Active Step, Lebanon, NH) to determine their preferred walking speed (Dingwell & Marin, 2006). Then, a total of seven Opal wearable sensors (APDM Inc, Portland, OR) were placed on the following locations: top and center of feet, shins with straps above the widest part of the gastrocnemius muscles, lower lateral side of thigh at midline, and the low back at the base of the spine. Next, participants walked for two conditions at their preferred walking speed. Condition 1 participants walked with the visual cue (adaptation) that was presented on the projection screen in front of the treadmill and were instructed to synchronize their gait to the visual cue via the following instructions "mimic the walking cue as closely as you can to the best of your ability": the Small Gait Asymmetry group received the visual cue exhibiting a small gait asymmetry with a ratio of 1.4-1 (i.e., the left side is moving about 40% faster than the right) and a large gait asymmetry ratio of 1.9-1 (i.e., the left side is moving about 90% faster than the right side) for an average treadmill speed of both belts at 1.24 m/s. Condition 2, participants walked either on the treadmill (i.e., retention) in the lab or ground level (i.e., transfer) in the Coleman gym. A five-minute seated rest period was provided between walking conditions to reduce the possibility of fatigue.

Statistical Analyses

All data analyses were performed using R (R, Version 4.2.3; R Foundation for Statistical Computing, Vienna, Austria). One-way ANOVAs were used to compare group demographics. All outcome variables were run through an R script to calculate gait asymmetries via the Symmetry Index Equation (**Figure 3**). After visually inspecting the data, some participants exhibited minimal changes while others exhibited obvious changes from baseline to adaptation. Therefore, participants were further divided into non-responder (i.e., ≤ 1% difference in all of the outcome variables) or responders (> 1% difference in at least one outcome variable).

The Shapiro-Wilks test (R package "rstatix") was utilized to assess the distribution of each outcome variable (SLS SI%, step duration SI %, and stride length SI%), which indicated the variables were non-normally distributed. Therefore, non-parametric Wilcoxon Signed Rank and Mann Whitney U tests (R package “stats”) were performed to compare gait asymmetry indices (SLS SI%, step duration SI %, and stride length SI%) at adaptation and post adaptation (i.e., retention and transfer) as well as between asymmetry groups. Only the 10th minute was used in the analyses. For all analyses, alpha level was set a priori at 0.05.

Results

Retention

One-way ANOVAs revealed a significant difference between preferred walking speed of the groups (*p* = 0.017) (**Table 2**). A post hoc test with Bonferroni correction showed the Control group had a faster preferred walking speed than the small and large retention responder groups (*p* = 0.046 and *p* = 0.018 respectively). Also, a significant difference was shown between leg length difference and groups (*p* = 0.044). The post hoc test revealed the small asymmetry non-responder group had a significantly larger leg length difference than the control group (*p* = 0.044). The Wilcoxon Signed Rank tests revealed in the small retention responder group from adaptation to retention that the single limb support SI % (V = 47, *p* = 0.049) and step duration SI % (V = 50, *p* = 0.02) decreased, but stride length SI % was not significantly different (V = 32, *p* = 0.70) (**Figure 9**). The Wilcoxon Signed Rank tests revealed significant decrease in the large retention responder group from adaptation to retention only for step duration SI % (V = 75, *p* = 0.04), while no significant differences were seen for single limb support SI % (V = 69, *p* = 0.11), and stride length SI % (V = 73, *p* = 0.057). The Wilcoxon Signed Rank tests revealed in the small retention non-responder group from adaptation to retention no statistically significant differences in single limb support SI % (V = 15, *p* = 0.438), step duration SI % (V = 15, *p* = 0.438), and stride length SI % (V = 17, *p* = 0.057) (**Figure 10**). The Wilcoxon Signed Rank tests revealed no significant differences in the large retention non-responder group from adaptation to retention for single limb support SI % (V = 5, *p* = 0.50), step duration SI % (V = 6, *p* = 0.25) and stride length SI % (V = 3, *p* = 1). As this group only had a sample size of three, confidence intervals could not be calculated. The Wilcoxon Rank sum tests (i.e., Mann Whitney U test) to compare the small and large retention responder groups on the gait asymmetry metrics revealed no statistical differences between groups on SLS SI % (W = 48, *p* = 0.157, CI[-∞, 0.324]), step duration SI % (W = 62, *p* = 0.44, CI[-∞, 1.012]), and stride length SI % (W = 76, *p* = 0.758, CI[-∞, 1.364)] (**Figure 11**). The control group showed no significant differences from adapt to retention for single limb support SI %, step duration SI % or stride length SI% (p > 0.05 for all variables) (**Figure 15**).

Transfer

One-way ANOVAs revealed a significant difference between preferred walking speed of the groups (*p* = 0.014) (**Table 3**). A post hoc test with Bonferroni correction showed the Control group had a faster preferred walking speed than the large transfer responder group (*p* = 0.027). The Wilcoxon Signed Rank tests revealed significant decreases in the small transfer responder group from adaptation to transfer in single limb support SI % (V = 54, *p* = 0.004) and stride length SI % (V = 54, *p* = 0.039). Step duration SI % (V = 50, *p* = 0.02) was not significantly different (V = 41, *p* = 0.193) (**Figure 12**). The Wilcoxon Signed Rank tests revealed significant decreases in the large transfer responder group from adaptation to transfer for single limb support SI % (V = 42, *p* = 0.004), step duration SI % (V = 45, *p* = 0.02), and stride length SI % (V = 42, *p* = 0.004). The Wilcoxon Signed Rank tests revealed in the small transfer non-responder group from adaptation to transfer no statistically significant differences in single limb support SI % (V = 13, *p* = 0.188), step duration SI % (V = 12, *p* = 0.313), and stride length SI % (V = 4, *p* =

0.438) (**Figure 13**). One participant in the small retention non-responder group was removed from the analyses because of a sensor error during the transfer condition. The Wilcoxon Signed Rank tests revealed no significant differences in the large transfer non-responder group from adaptation to transfer for step duration SI % (V = 22, $p = 0.219$) and stride length SI % (V = 24, $p = 0.109$), while single limb support SI % significantly decreased (V = 27, $p = 0.031$). The Wilcoxon Rank sum tests (i.e., Mann Whitney U test) to compare the small and large transfer groups responders on the gait asymmetry metrics revealed no statistical differences between groups on SLS SI % (W = 41, $p = 0.39$, CI[-∞, 0.508]), step duration SI % (W = 39, $p = 0.863$, CI[-∞, 0.863]), and stride length SI % (W = 59, $p = 0.879$, CI[-∞, 0.80)] (**Figure 14**).

Table 2. Participant Demographics- Retention Groups - means (SE)

Variables	SR res (*n* = 10)	SR nr (*n* = 6)	LR res (*n* = 13)	LR nr (*n* = 3)	Con (*n* = 8)	*p*
Age (years)	22.63 (1.13)	23.69 (3.19)	23.63 (1.38)	30.86 (3.22)	26.16 (2.37)	0.134
Height (cm)	167.83 (3.90)	164.78 (3.58)	167.87 (2.65)	170.67 (2.33)	168.2 (3.77)	0.733
Weight (kg)	73.26 (5.05)	60.33 (4.08)	69.75 (2.56)	87.69 (1.66)	69.97 (2.79)	0.662
Speed (m/s)	0.88 (0.04)	0.91 (0.04)	0.85 (0.06)	0.86 (0.06)	1.14 (0.09)	0.017*
Left leg length (cm)	88.15 (2.30)	86.97 (2.06)	87.85 (1.85)	88.43 (1.49)	88.6 (2.10)	0.801
Right leg length (cm)	87.93 (2.31)	87.72 (2.17)	87.87 (1.91)	88.13 (1.33)	88.68 (2.13)	0.797
Leg length difference (cm)	0.56 (0.10)	0.78 (0.15)	0.35 (0.07)	0.63 (0.05)	0.30 (0.07)	0.044*

Note. SR res = Small Asymmetry Retention Responder group, SR nr = Small Asymmetry Retention Non-Responder group, LR res = Large Asymmetry Retention Responder group, LR nr = Large Asymmetry Retention Non-Responder group, and Con = control group.
* Indicates $p < 0.05$

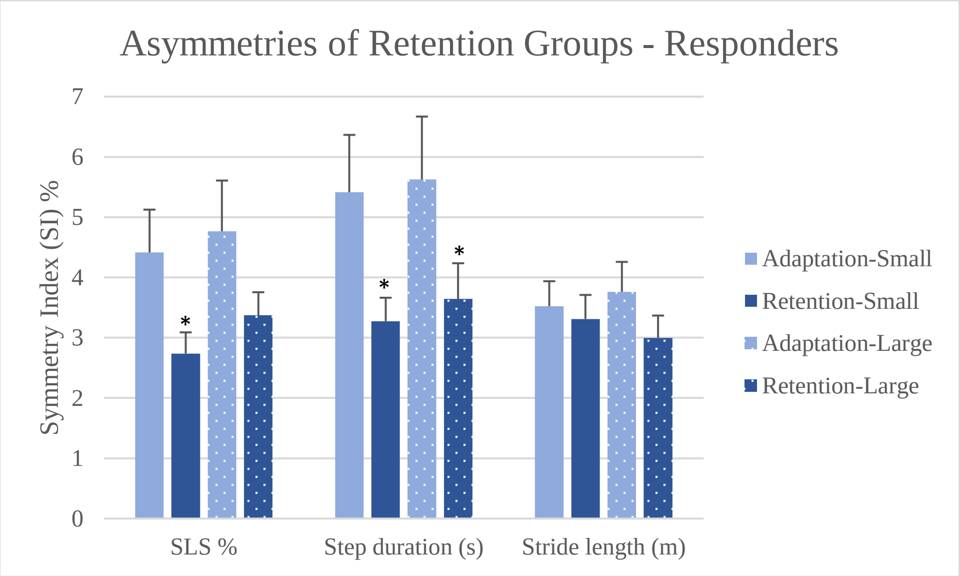
Table 3. Participant Demographics- Transfer Groups – means (SE)

Variables	ST res (*n* = 10)	ST nr (*n* = 6)	LT res (*n* = 9)	LT nr (*n* = 7)	Con (*n* = 8)	*p*
Age (years)	25.54 (2.57)	21.54 (1.12)	23.48 (1.44)	20.95 (0.64)	26.16 (2.37)	0.950
Height (cm)	168.75 (2.83)	167.85 (2.04)	168.11 (3.20)	168.57 (1.75)	168.2 (3.77)	0.942
Weight (kg)	67.18 (4.78)	75.67 (5.99)	72.98 (7.91)	70.83 (2.02)	69.97 (2.79)	0.839
Speed (m/s)	0.89 (0.06)	0.94 (0.08)	0.83 (0.04)	1.01 (0.04)	1.14 (0.09)	0.014*
Left leg length (cm)	88.65 (2.03)	89.65 (1.14)	87.44 (2.04)	89.70 (0.94)	88.6 (2.10)	0.989
Right leg length (cm)	88.81 (2.16)	89.78 (1.20)	87.50 (2.19)	89.54 (0.99)	88.68 (2.13)	0.955
Leg length difference (cm)	0.46 (0.09)	0.33 (0.09)	0.43 (0.12)	0.44 (0.10)	0.30 (0.07)	0.454

Note. ST res = Small Asymmetry Transfer Responder group, ST nr = Small Asymmetry Transfer Non-Responder group, LT res = Large Asymmetry Transfer Responder group, LT nr = Large Asymmetry Transfer Non-Responder group, and Con = control group.

* Indicates $p < 0.05$

Figure 9. Comparison of Adaptation to Retention in the Responder Groups – means (SE)

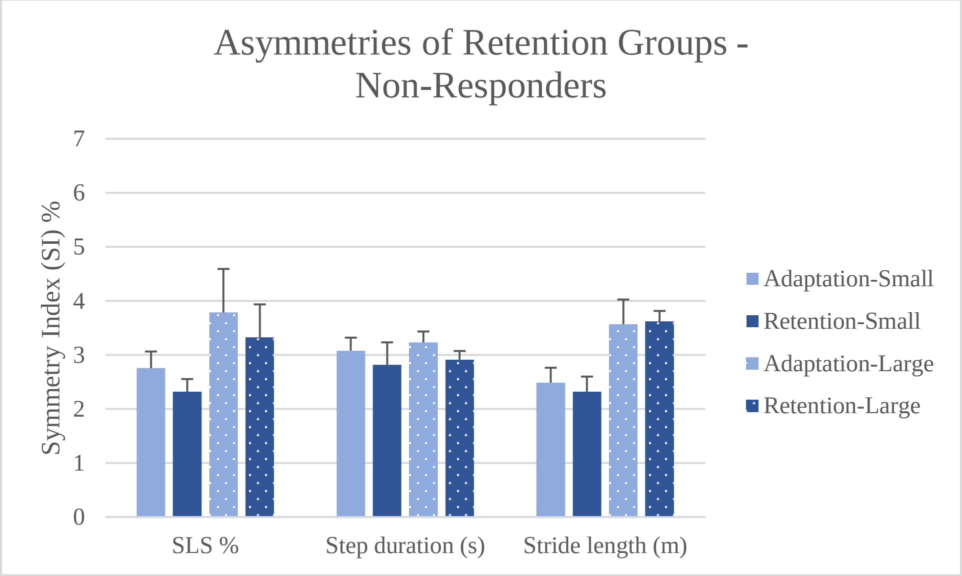


Note. SLS % SI % = Single limb support %.

* Indicates $p < 0.05$

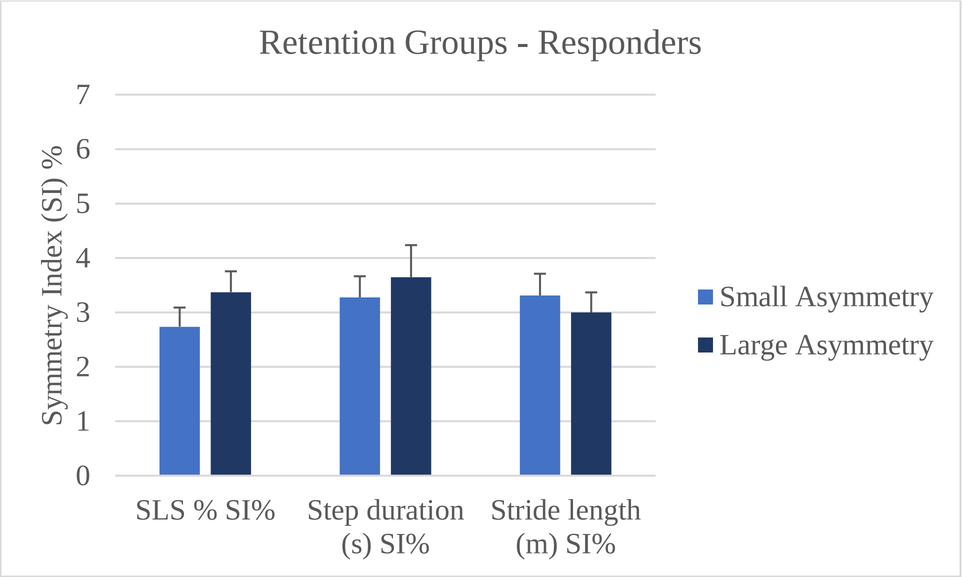
** Indicates $p < 0.01$

Figure 10. Comparison of Adaptation to Retention in the Non-Responder Groups – means (SE)



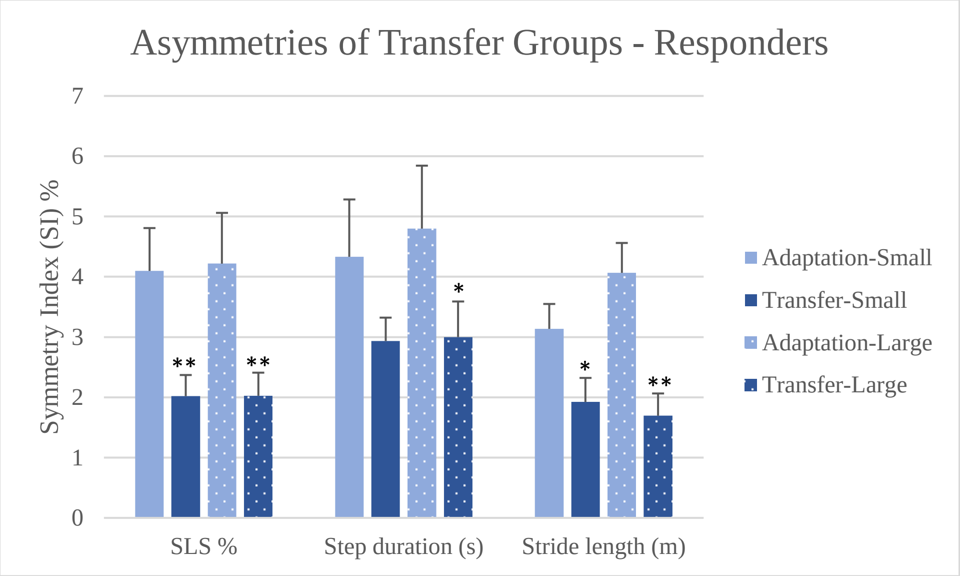
Note. SLS % SI % = Single limb support %.

Figure 11. Comparison of Small and Large Retention Responder groups - means (SE)



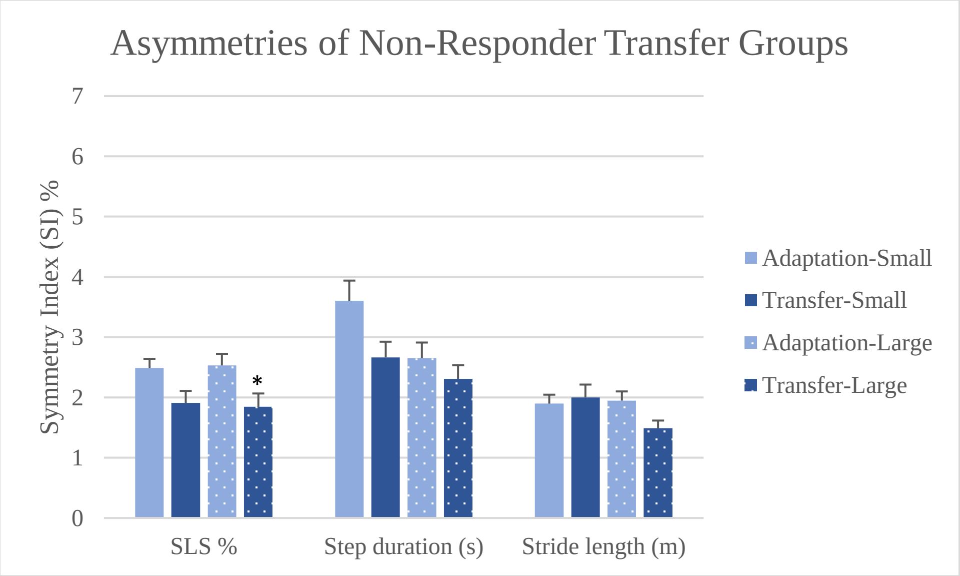
Note. SLS % SI % = Single limb support %.

Figure 12. Comparison of Adaptation to Transfer in the Responder Groups – means (SE)



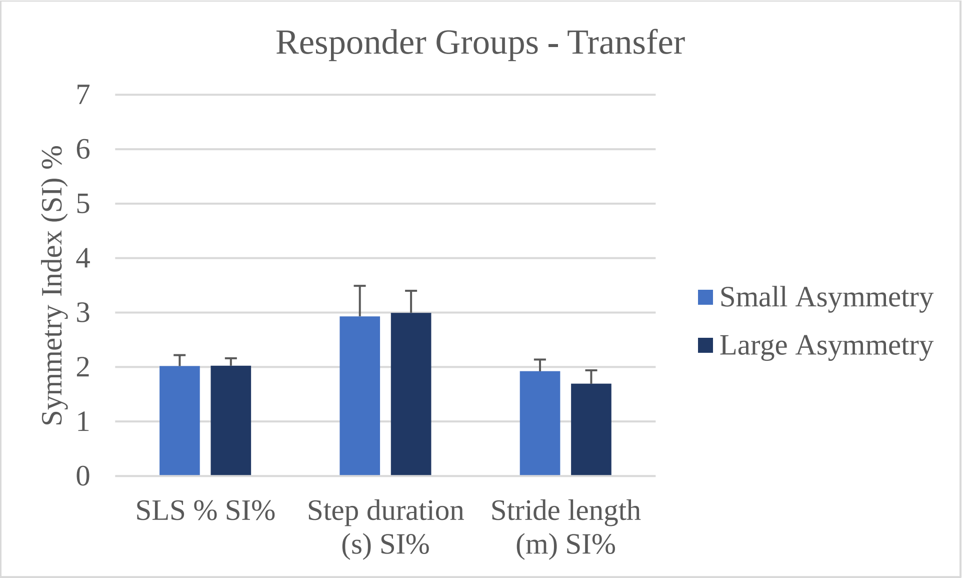
Note. SLS % SI % = Single limb support %.
* Indicates $p < 0.05$
** Indicates $p < 0.01$

Figure 13. Comparison of Adaptation to Transfer in the Non-Responder Groups – means (SE)



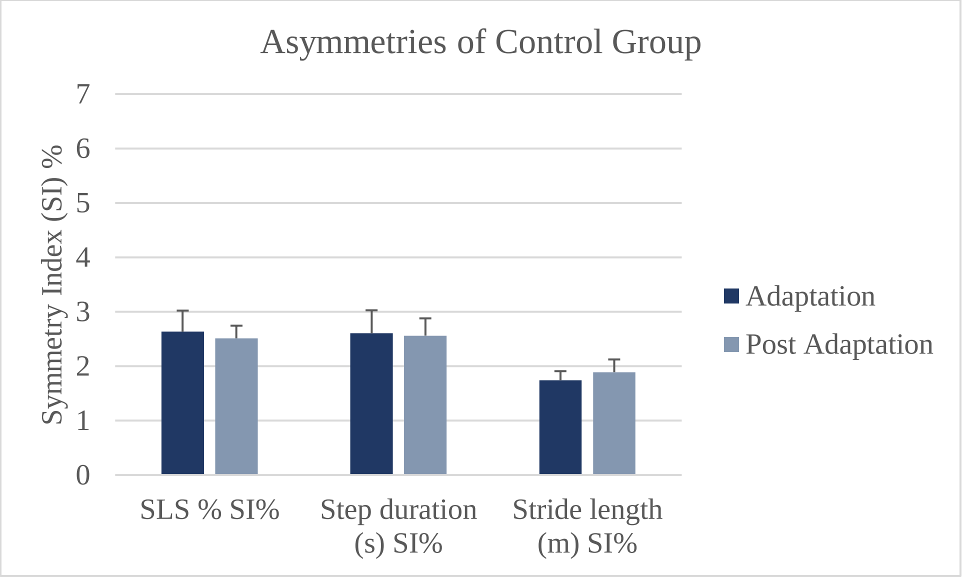
Note. SLS % SI % = Single limb support %.
* Indicates $p < 0.05$

Figure 14. Comparison of Small and Large Transfer Responder groups - means (SE)



Note. SLS % SI % = Single limb support %.

Figure 15. Comparison of Adaptation to Retention in Control group - means (SE)



Note. SLS % SI % = Single limb support %.

Discussion

The first aim of this study was to explore if the asymmetric walking pattern was retained after the visual cue was removed. We hypothesized participants would retain the gait asymmetries after the visual cue was removed. Our hypothesis was partially supported. The large retention responder group showed no statistically significant differences in single limb support SI% or stride length SI%, suggesting that the asymmetrical pattern was retained. However, step duration SI% did significantly decrease in the large asymmetry responder group indicating certain spatiotemporal metrics may be more likely to be retained. Our findings are consistent with the split-belt treadmill training, as changes in asymmetry of step length and double support time are commonly seen during retention (Reisman et al., 2007; Roemmich, Hack, et al., 2014). Ryan and colleagues (2020) reported the participants who targeted step length symmetry improved asymmetries, yet participants who trained to target stance time symmetry did not reduce asymmetries.

The small retention responder group also had significantly reduced gait asymmetries, specifically single limb support SI% and step duration SI%, indicating the small retention group responders did not retain the asymmetric walking pattern. However, stride length SI% did not change, which may seem as though this metric was retained, but in our earlier study we did not see any changes from baseline to adaptation in the small asymmetry groups for stride length SI%. To our knowledge, no studies have examined gait adaptation training using less than a 2-1 ratio. The lack of retention may be due to participants not perceiving asymmetry with the small asymmetrical cue during adaptation as Reisman (2005) reported all their participants perceived asymmetry in early adaptation of the split-belt treadmill training that showed changes post training. We also hypothesized the large gait asymmetry groups would exhibit greater gait asymmetries during retention than the small gait asymmetry groups. Our hypothesis was not supported as the small and large asymmetry group responders did not significantly differ during retention. This was surprising as some metrics in the large retention responder group did not change compared to the small retention responder group that showed changes, suggesting the asymmetrical pattern was mainly retained only in the large retention responder group. However, the small asymmetric visual cue had an asymmetric ratio that was subthreshold of what is clinically observable. Split-belt treadmill training typically uses a 2-1 asymmetry ratio (Reisman et al., 2007, 2013). Thus, the small visual cue might not have been enough to elicit retention that is typically seen with split-belt treadmill training. Although, the lack of difference between the small and large group responders could be due to a small sample size.

The second aim of this study was to examine if the asymmetrical walking pattern transferred to overground walking. We hypothesized gait asymmetries would persist in overground walking. However, our hypothesis was not supported as nearly all gait asymmetries were reduced for both the small and large responder groups. This study focused on the 10th minute, which may be a reason we didn’t see transfer of the asymmetries at the last minute of adaptation. The literature indicates healthy adults can retain altered gait patterns but in overground training participants return to baseline within minutes of the transfer condition in healthy adults (Shideler et al., 2021). Also, we hypothesized the large gait asymmetry groups would exhibit greater gait asymmetries than the small gait asymmetry groups during transfer to overground walking. Our hypothesis was not supported as no differences were found between any of the gait asymmetry variables when comparing small to large asymmetry responder groups. The lack of transfer may be due to a healthy system that is returning back to a stable state (J. A. Scott Kelso, 1995).

The motor learning literature suggests multiple trials over several days and randomly order practice (i.e., practice variability) may enhance learning and retention of the motor task (Czyż, 2021; Savion-Lemieux & Penhune, 2005; Schmidt et al., 2019). However, our study was a one-day study with only 10 minutes of adaptation as this study was a proof of concept of the methodology. This study primarily used an attentional focus cue via the asymmetry visual cue and instructions, to enhance optimization of the asymmetric walking pattern similar to Lewek and colleagues (2018) using instruction to optimize symmetry during split-belt treadmill training. Other motor learning principles such as knowledge of performance can improve motor tasks relative to knowledge of results may be an important factor influencing gait adaptation that is not seen in the gait literature (Sharma et al., 2016; Wulf et al., 2010). Motor learning literature for feedback and attentional focus cues in retention and transfer of gait adaptation training is very limited and should be considered in designing gait adaptation studies.

A few limitations exist in this study. Our sample size became quite small once retention and transfer groups were further divided into responder and non-responders. Retention was very short term since this was a one-day study and only a five-minute rest period was provided between adaptation and retention. We did not examine overground walking patterns prior to gait adaptation to compare to transfer after training, which may better capture transfer of the gait pattern.

Our findings were similar to split-belt treadmill training studies for retention but not transfer with gait adaptation training. Some gait asymmetries remained elevated during retention suggesting the asymmetrical visual cues may be an alternative to split-belt treadmill training. The lack of transfer of the adopted pattern may be indicative of a healthy system. Future work should expand to include clinical populations to test and improve the methodology to reduce gait asymmetries.

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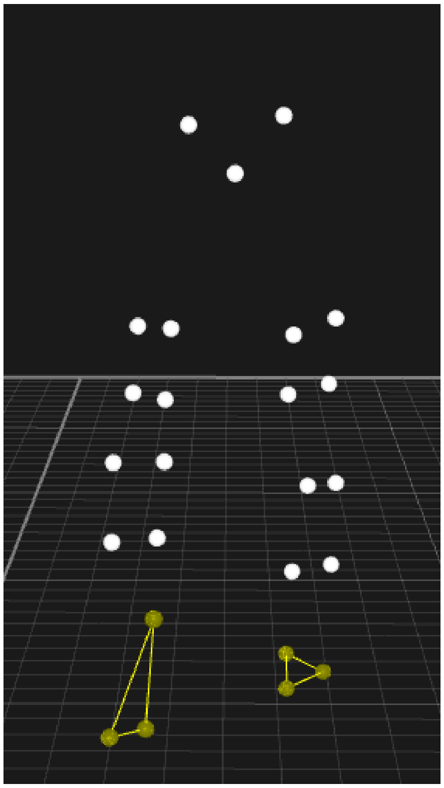
APPENDIX A: VISUAL CUE QUESTIONNAIRE

1. What part of the visual cue did you focus on? **Please circle the location(s).**



To answer the questions below, a scale is available in the form of a line. Please mark the appropriate point on the line with a cross, which best describes how you felt. Please use only a cross on the line, do not write text.

2. How even did you feel *during* walking with the visual cue?

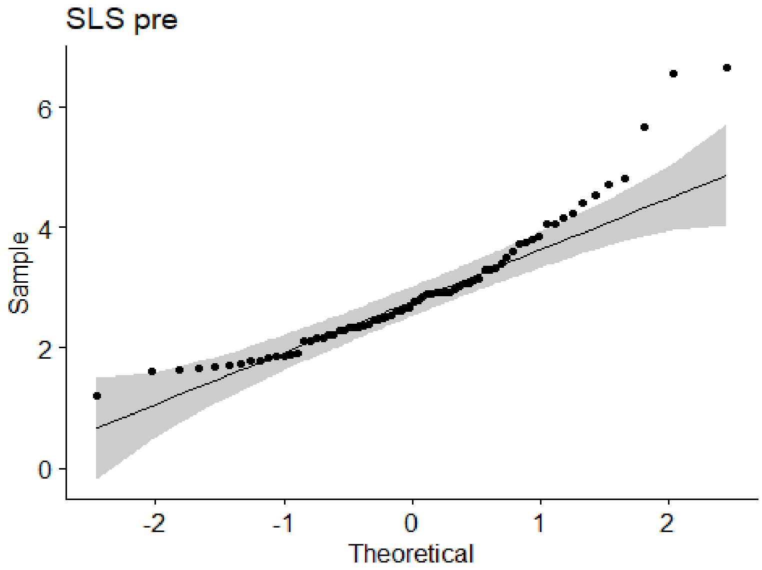
Completely Even ______________________________ Completely Uneven

3. How even did you feel walking *after* the visual cue was removed?

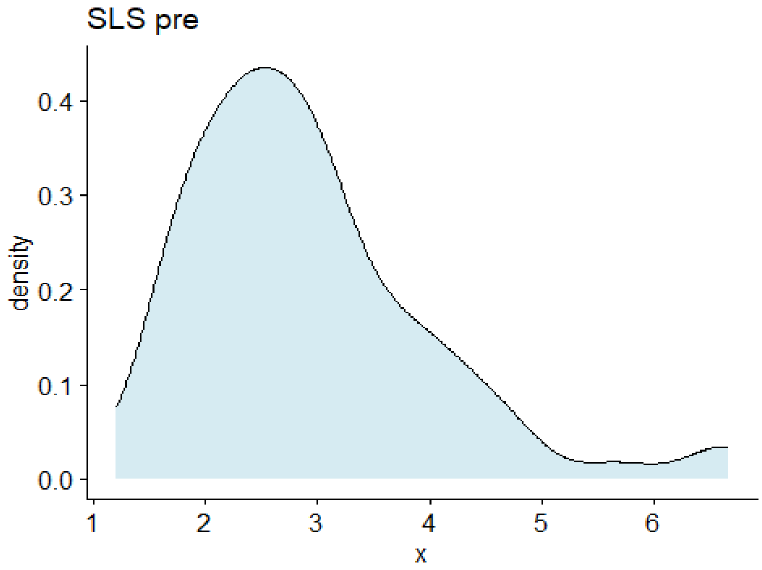
Completely Even ______________________________ Completely Uneven

APPENDIX B: RAW DISTRIBUTION OF GAIT ASYMMETRY VARIABLES

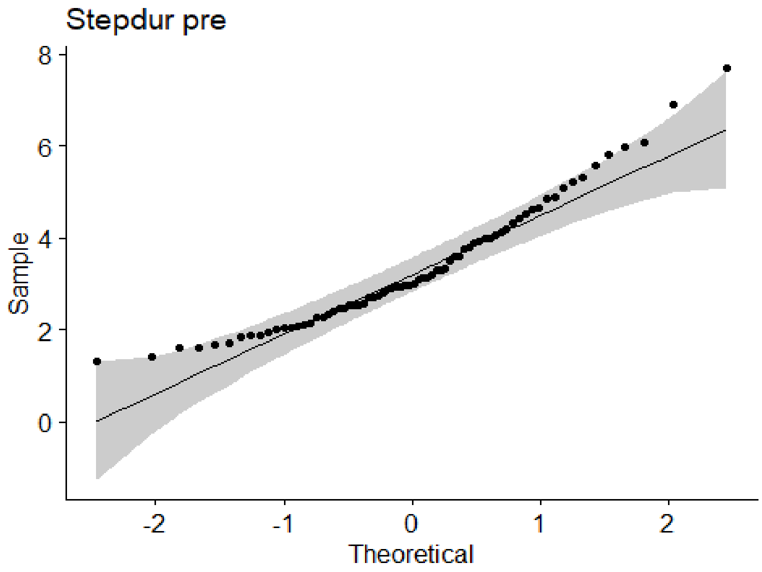
Q-Q plot Single Limb Support asymmetry Baseline



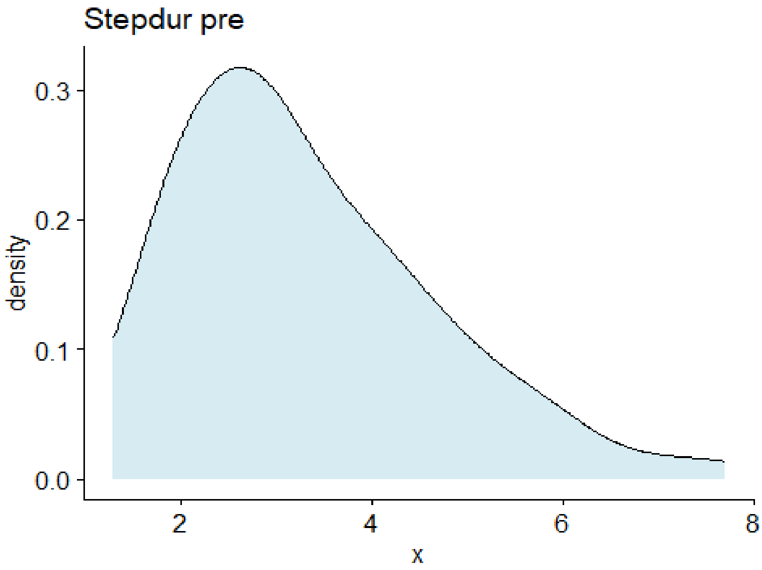
Density plot Single Limb Support asymmetry Baseline



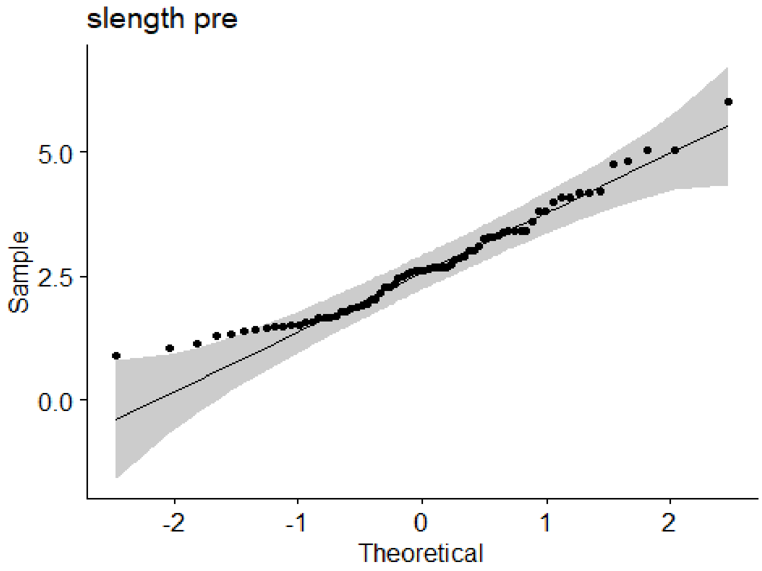
Q-Q plot step duration asymmetry Baseline



Density plot step duration asymmetry Baseline

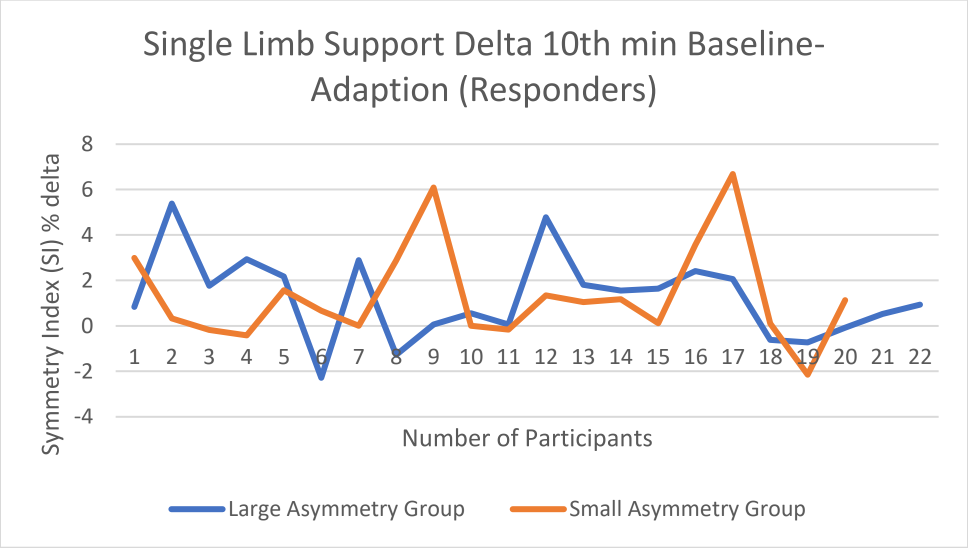


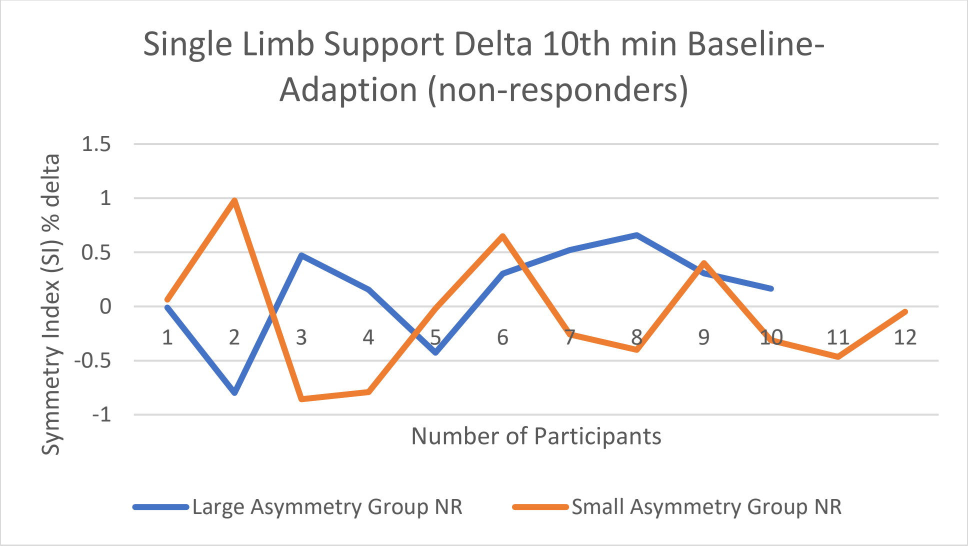
Q-Q plot stride length asymmetry Baseline

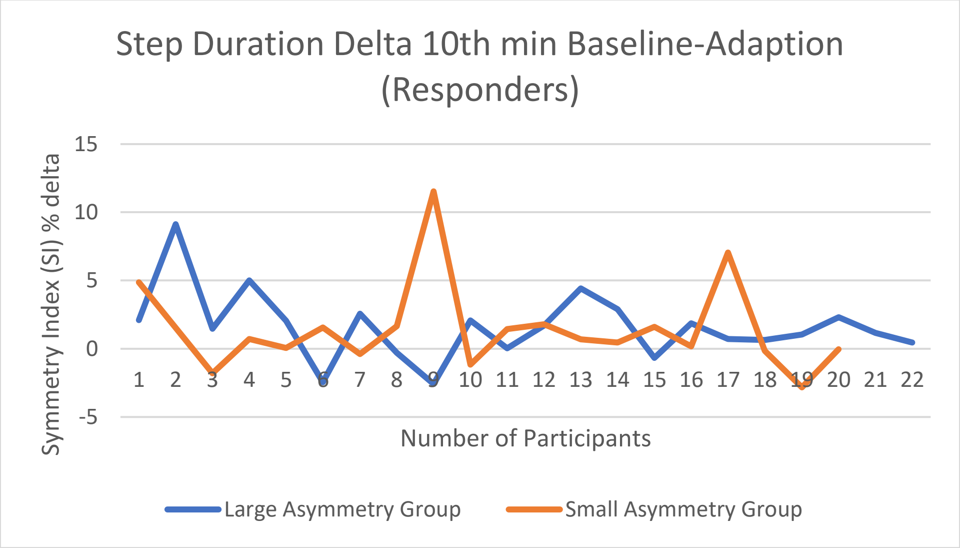


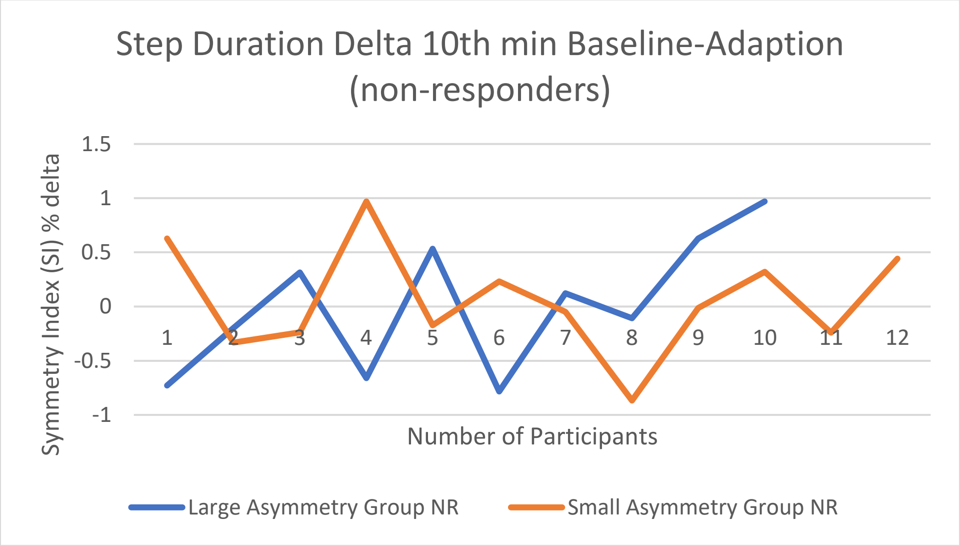
Density plot step duration asymmetry Baseline

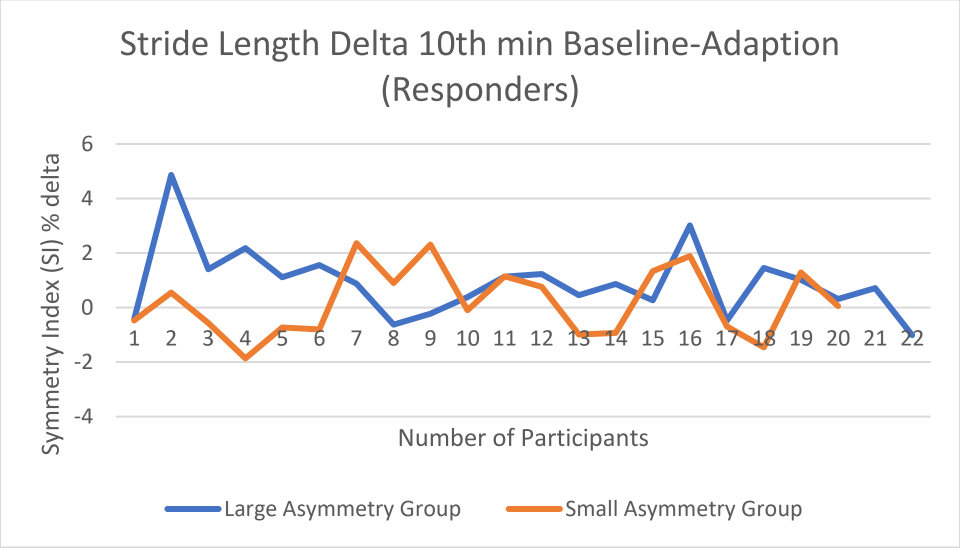
APPENDIX C: GRAPHS OF RESPONDERS AND NON-RESPONDERS

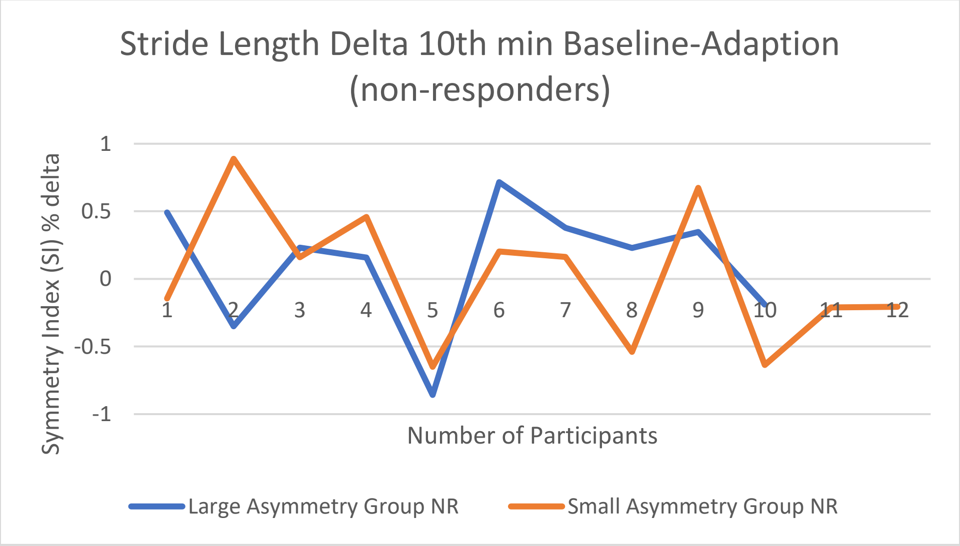




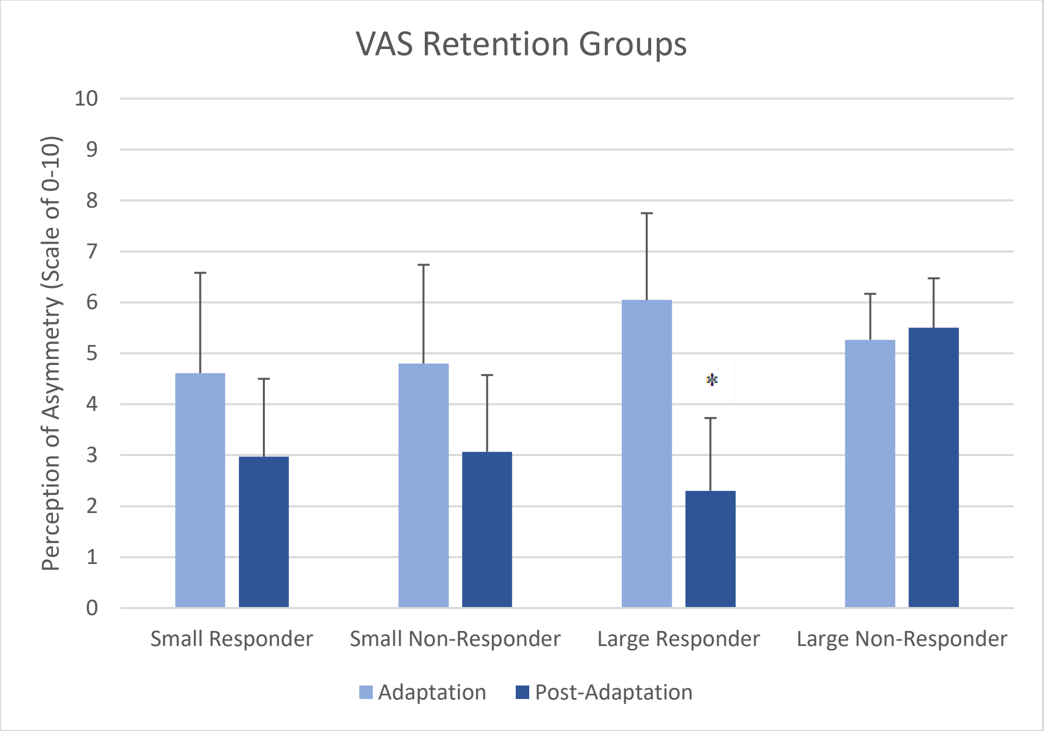

Step Duration Delta 10th min Baseline-Adaption (Responders)
Symmetry Index (SI) % delta
15
10
5
0
-5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Number of Participants
Large Asymmetry Group
Small Asymmetry Group

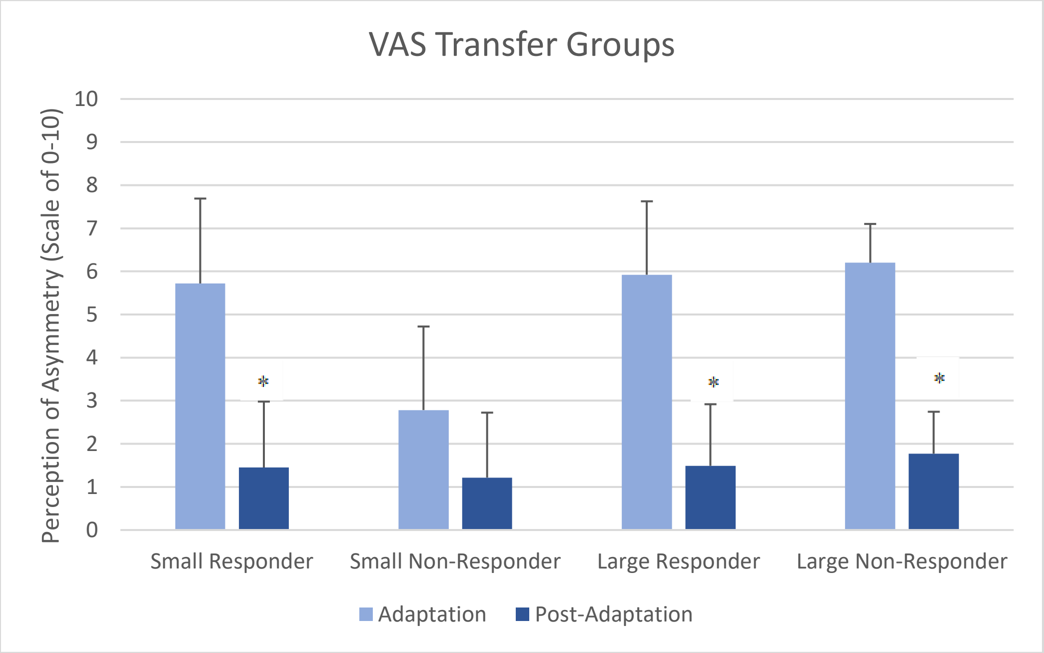

Step Duration Delta 10th min Baseline-Adaption (non-responders)
Symmetry Index (SI) % delta
1.5
1
0.5
0
-0.5
-1
1 2 3 4 5 6 7 8 9 10 11 12
Number of Participants
Large Asymmetry Group NR
Small Asymmetry Group NR


Stride Length Delta 10th min Baseline-Adaption
(Responders)
Symmetry Index (SI) % delta
6
4
2
0
-2
-4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Number of Participants
Large Asymmetry Group
Small Asymmetry Group

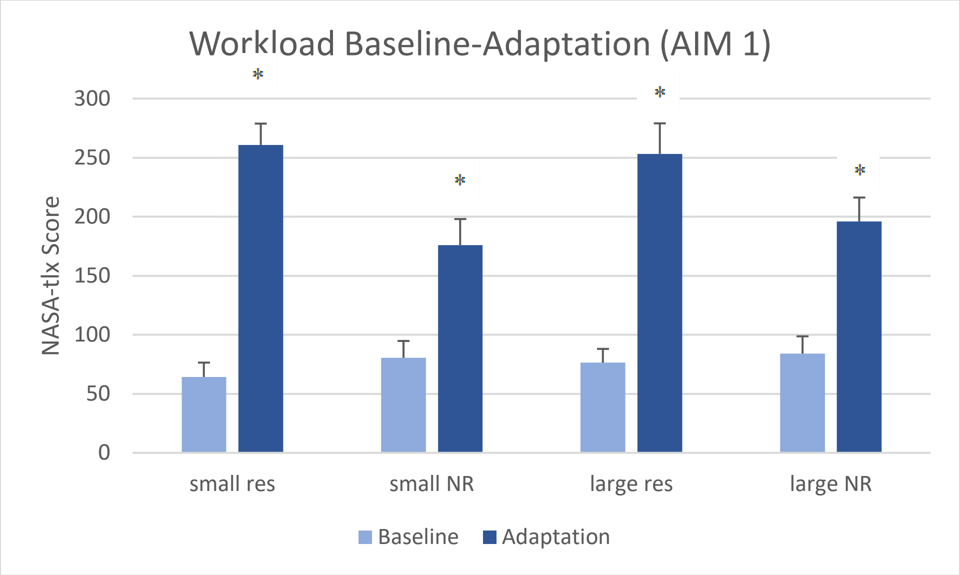

Stride Length Delta 10th min Baseline-Adaption
(non-responders)
Symmetry Index (SI) % delta
1
0.5
0
-0.5
-1
1 2 3 4 5 6 7 8 9 10 11 12
Number of Participants
Large Asymmetry Group NR
Small Asymmetry Group NR

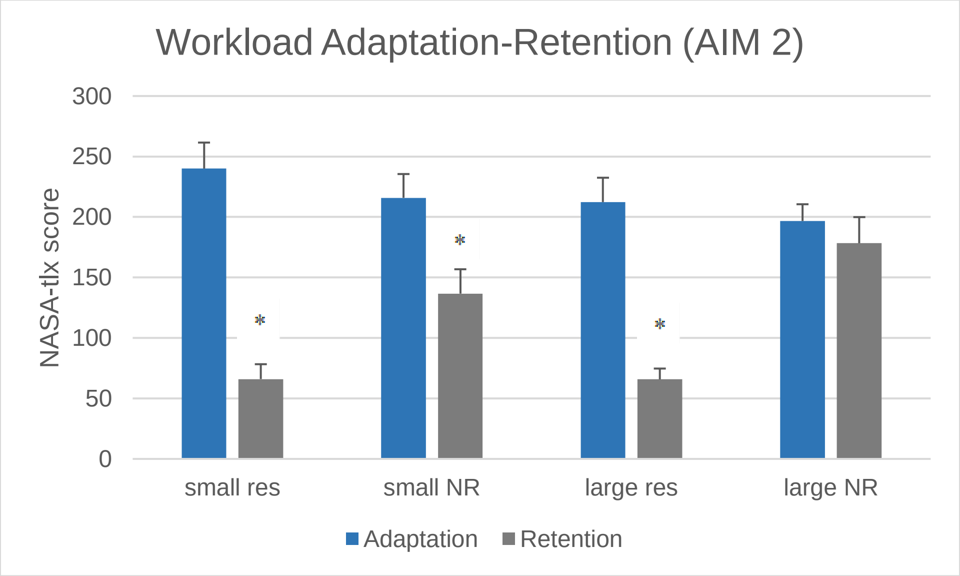
APPENDIX D: VISUAL CUE VAS SCORES

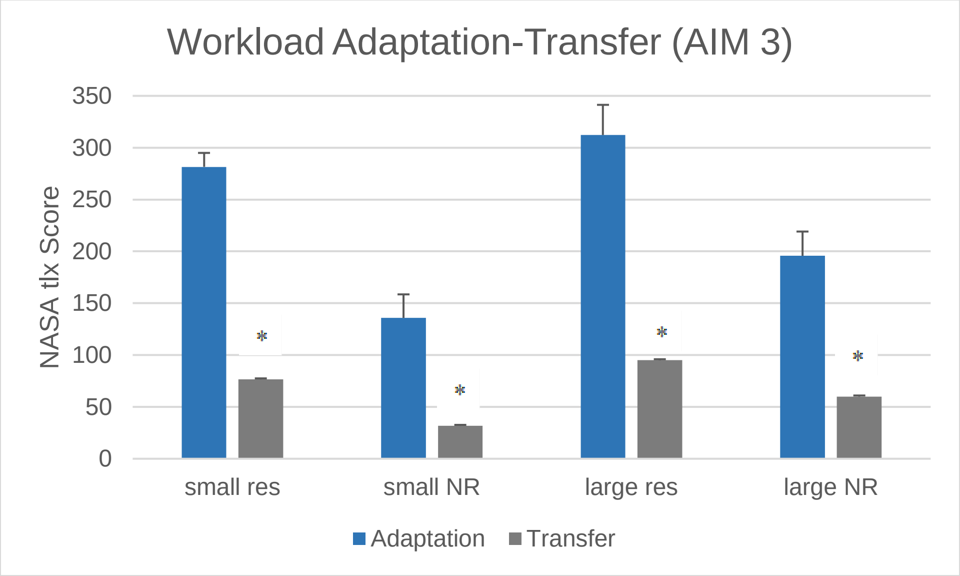




APPENDIX E: NASA-TLX SCORES






Workload Adaptation-Transfer (AIM 3)
NASA tlx Score
350
300
250
200
150
100
50
0
*
*
*
*
small res
small NR
large res
large NR
Adaptation
Transfer