The Use of Visual Feedback to Improve Temporal Gait Asymmetry Post-Stroke

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
Rehabilitation Sciences Institute
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Abstract

Temporal gait asymmetry (TGA) is common post-stroke and particularly resistant to conventional therapy. Therefore new rehabilitation approaches are required. One approach may be visual feedback (FB) during gait training. Optimal parameters for providing visual FB during motor skill acquisition are well established for healthy adults but remain largely unknown for motor learning in people with stroke. This study aimed to determine the effect of visual displays and frequencies for visual FB about TGA during an overground walking practice session and its effects during a retention session. Participants received feedback at 50% or 100% frequency in one of two display formats (A and B). The largest effect sizes were seen in the group that received Display B at 100%, and 50%. Individuals that received FB during practice showed significant changes in TGA at the retention while those individuals who did not receive feedback showed no changes at retention.
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<th>Description</th>
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<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
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<tr>
<td>CMSA</td>
<td>Chedoke McMaster Stroke Assessment</td>
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<td>CPG</td>
<td>Central Pattern Generator</td>
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<td>DLS</td>
<td>Double Limb Support</td>
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<td>EMG</td>
<td>Electromyography</td>
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<td>GC</td>
<td>Gait Cycle</td>
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<td>GRF</td>
<td>Ground Reaction Force</td>
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<td>HRQoL</td>
<td>Health Related Quality of Life</td>
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<td>HS</td>
<td>Heel Strike</td>
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<td>IC</td>
<td>Initial Contact</td>
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<tr>
<td>IQR</td>
<td>Interquartile Range</td>
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<tr>
<td>KP</td>
<td>Knowledge of Performance</td>
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<td>KP</td>
<td>Knowledge of Results</td>
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<tr>
<td>LE</td>
<td>Lower Extremity</td>
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<tr>
<td>MoCA</td>
<td>Montreal Cognitive Assessment</td>
</tr>
<tr>
<td>NDT</td>
<td>Neurodevelopmental Technique</td>
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<tr>
<td>NIHSS</td>
<td>National Institute of Health Stroke Scale</td>
</tr>
<tr>
<td>RAS</td>
<td>Rhythmic Auditory Stimulation</td>
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<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<td>Abbreviation</td>
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<tr>
<td>SLS</td>
<td>Single Limb Support</td>
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<td>TGA</td>
<td>Temporal Gait Asymmetry</td>
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1 Overview

Mobility challenges are common after stroke, with almost 80% of people still experiencing impaired walking function 3 months post-stroke\(^1\). Recovery of walking function is one of the most commonly stated goals of patients\(^2\), however 22% of those who experience walking impairments do not regain any walking function by the end of rehabilitation\(^3\). Many of those that do regain walking function have continued gait related impairments or deviations such as decreased velocity\(^4,5\), difficulty with balance\(^6\), increased energy cost\(^7\) and spatiotemporal gait asymmetry\(^8\). These persistent gait impairments can contribute to a decline in mobility\(^9,10\), increased dependence and reduced health related quality of life (HRQoL)\(^11\).

Rehabilitation is often discontinued for patients when they no longer exhibit motor improvements, or “plateau”, and further improvements are deemed unlikely\(^12\). However, improvements seen in chronic stroke patients with the use of novel interventions\(^13^-^17\) rebuts the supposed motor recovery plateau. It has been suggested that the plateau is not indicative of limited capacity for recovery, but rather a neuromuscular adaptation to motor interventions\(^18\). New interventions are required to address persistent gait impairments and enable patients to overcome the motor recovery plateau. One approach may be to apply the principles of motor learning to post-stroke gait rehabilitation.

Principles of the use of augmented visual feedback to facilitate motor skill learning were applied in this study. Feedback is often provided during rehabilitation therapy, however, not in
the most effective format\textsuperscript{19}. The purpose of this study was to investigate the effects of visual feedback on post-stroke gait, specifically, temporal gait asymmetry (TGA). This study employed a motor learning experimental paradigm that included a single acquisition session where visual feedback was given during overground walking practice and a retention session 24 hours later where TGA was assessed during overground walking without feedback.
2 Literature Review

2.1 Stroke Overview

2.1.1 Stroke in Canada

Stroke is the leading cause of disability in Canada, with 50,000 new strokes each year\textsuperscript{20}. There are 412,000 survivors living with the effects of stroke, and this is expected to rise to between 666,000 and 738,000 by the year 2038\textsuperscript{21} due to Canada’s growing and aging population. Every individual experiences the effects of stroke differently, which can manifest both physically and cognitively. Some physical effects of stroke include muscle weakness, spasticity, and loss or change in sensation causing challenges with movement, mobility, and balance\textsuperscript{22}. Cognitive effects of stroke can include difficulty with thinking, memory and emotions\textsuperscript{23,24}. Rehabilitation after stroke is aimed at mitigating physical and cognitive impairments, and increasing independence and health related quality of life (HRQoL)\textsuperscript{25}.

Despite rehabilitation efforts, many survivors of stroke never fully recover. Approximately 36\% experience significant disability related to stroke impairments that persists 5 years post-stroke\textsuperscript{26} and more than 40\% require ongoing assistance with activities of daily living (ADLs)\textsuperscript{27}. With the estimated number of individuals experiencing the effects of stroke in Canada expected to rise substantially over the next years these outcomes are of increasing concern.
2.2 Course of Recovery

2.2.1 General Course of Recovery

Recovery after stroke is the re-emergence of structures and functions as they existed previous to neurologic injury. Recovery is highly individual and is related to a variety of factors such as site and size of the lesion in the brain, severity of initial motor impairment, and age. Recovery is generally rapid during the sub-acute phase and tapers to a plateau in the chronic phase. The largest improvements are seen during the first 3 months following the stroke. These rapid improvements are seen in all areas including upper extremity function, walking and ability to perform ADLs. These improvements continue up to 6 months although at a less significant rate. At around six months, recovery begins to plateau with little if any improvements seen, especially after one year. However, there is evidence from numerous studies of improved function in the chronic phase of stroke recovery and the capacity for continued neuroplasticity has been demonstrated. There are a variety of interventions administered at least one year post-onset that have improved daily functioning and motor recovery of the upper and lower extremities (LE).

2.2.2 Recovery of Gait

Impaired walking function is common after stroke, with half of survivors having no walking function immediately following stroke and almost 80% still experiencing walking dysfunction after the first 3 months. Improvement in walking, as measured by the Barthel index for
walking, occurs in the first 11 weeks\textsuperscript{3}, with little change seen after 6 months of onset\textsuperscript{3,39,41,50}. The speed of gait recovery can be linked to the initial degree of paresis and walking ability (e.g. independence, velocity, endurance), with faster recovery seen in those with milder paresis and greater walking ability in the first week post-stroke\textsuperscript{3,10,51,52}. Of those whose walking function was affected at onset, 64\% will regain walking independence\textsuperscript{3,53}, 14\% will be able to walk with assistance, and 22\% will not recover walking function\textsuperscript{3} by the end of rehabilitation. It is important to note that the studies reporting these outcomes used functional scales, which measure level of assistance required while walking (e.g. dependent versus independent), and do not consider other features of gait impacted by stroke, such as velocity, endurance, symmetry and loading. While it is believed that very little improvement is seen after 6 months, there is increasing evidence for improving gait velocity and endurance at the chronic stage\textsuperscript{9,54,55}.

2.3 Gait

2.3.1 Normal Gait

Gait is a cyclical and complex sequence of movements that carries an individual from one point to another by propelling the body forward, while maintaining upright stability\textsuperscript{56}. Human locomotion is dependent on stance stability despite constantly changing posture\textsuperscript{57}, propulsion through muscle and joint activation\textsuperscript{58,59}, shock absorption to minimize impact\textsuperscript{60}, and energy conservation\textsuperscript{61}, for performance efficiency. These four variables enable locomotion to occur through alternation of body weight support and limb propulsion between the limbs. A single
set of support and propulsion actions of one limb is called a gait cycle (GC). A GC can then be further divided into phases: stance and swing. A GC can be analyzed spatially or temporally. Spatial characteristics of gait include step length (i.e., the distance traveled by one limb in a step) and step width (i.e., distance between two feet in a step), but for the purposes of this thesis, the primary focus will be on temporal factors. Stance is the period in which one limb maintains contact with the ground to support the body, while swing is the period in which one limb moves through space in a forward motion to advance position. Swing begins when the foot is lifted and the toes no longer have any contact with the ground, commonly referred to as toe-off (TO), and ends when the same foot makes contact again with the heel, commonly referred to as heel strike (HS) or initial contact (IC). The distance between HS of one foot to HS of the opposite foot is the step length, while stride length is the distance from HS of one foot to the next consecutive HS of the same foot. Stance begins at IC and ends at TO, during which ground contact is maintained.

The stance phase can be further divided into three parts. At the time of HS, the opposite limb still has contact with the ground to facilitate the transfer of weight to the other limb. This is a period where the body is supported by both limbs called initial double limb support (DLS). Once support has been transferred to the limb that has just initiated floor contact, the opposite limb enters swing phase, and no longer has contact with the floor. At this point, the body is being supported by only one limb, and is called single limb support (SLS). When the opposite limb completes swing phase and HS occurs, this marks the end of SLS and the beginning of DLS.
2.3.2 Neural Control of Walking

The underlying processes controlling human locomotion are believed to be a combination of central pattern generators (CPG), descending neural pathways and peripheral sensory feedback\(^{63,64}\). However, much of this knowledge was ascertained from the study of animal models, leaving the exact nature of human locomotor control debated\(^{64-67}\). The CPG is a neuronal circuit within the spinal cord that operates independently of descending neural input able to produce the rhythmical motor patterns through flexor and extensor motor neuron activation\(^{69}\). While the CPG is able to produce the rhythmical basis of locomotion, supraspinal and peripheral sensory information is required for creating a flexible motor pattern\(^{63,64}\), capable
of spatial and temporal adaptation to extrinsic environmental factors. It is believed that the importance and role of this descending and peripheral information for the control of locomotion is greater in humans than the animal models of CPG frequently studied. Neural control of walking can be impacted by lesions to various structures of the central nervous system that disrupt the automaticity and patterning of gait. Injury to the motor cortex, and descending motor pathways can result in paresis and hypertonicity, while injury to somatosensory cortex can interfere with sensory feedback. These neurologic injures lead to the gait deviations observed in post-stroke gait.

2.3.3 Common Gait Deviations Post-Stroke

Factors that contribute to gait deviations post-stroke have been characterized using electromyography (EMG), kinetic, kinematic, and spatiotemporal measures. The most widely reported spatiotemporal measure of gait after stroke is velocity, which is typically decreased compared to neurotypical gait. This slower gait is also characterized by decreased cadence and longer gait cycle. Other spatiotemporal characteristics of gait such as step length, swing and stance time, and double support time may change after stroke, and can exhibit interlimb differences.

The earliest EMG studies of post-stroke gait identified atypical motor performance of the paretic and nonparetic side, with marked decrease in EMG activation on the paretic side, increased activation on the nonparetic side, and atypical timing of EMG onset. As is the case with many characteristics of stroke, there is great interindividual variation in muscle
activation patterns, although there are some patterns that are exhibited more often\textsuperscript{74,80,81}.

Knutsson and Richards\textsuperscript{80} attempted to identify common EMG patterns across individuals, resulting in three classifications. Type I (spastic gait) demonstrates an early activation of the calf muscles of the paretic limb during stance phase due to hyperactive stretch reflexes as the knee is extended at initial contact. Type II (paretic gait) is evidenced by a decrease in muscle activation of two or more muscle groups of the paretic limb. Type III is characterized by atypical co-activation of muscle groups, but not an increase or decrease in muscle activity. While these classifications are limited in profiling the diversity of post-stroke gait\textsuperscript{82}, the general pattern holds that atypical amplitude and timing are common characteristics of post-stroke EMG activity\textsuperscript{74,81,83–85}.

Post-stroke gait also exhibits kinetic and kinematic abnormalities, compared to that of a healthy individual. Slower gait in healthy individuals is marked by smaller joint excursions and force production\textsuperscript{86,87} and similar deviations are seen in the typically reduced speed of post-stroke gait\textsuperscript{88–90}. The most common kinematic deviations of the paretic limb are increased ankle plantar flexion at initial contact, knee hyperextension at weight acceptance and stance phase, decreased knee flexion and dorsiflexion through swing phase, hip hiking or circumduction, and increased external rotation of the hip and ankle\textsuperscript{74,83,89,91}. Furthermore, ground reaction force (GRF) is significantly reduced in the paretic limb compared to the nonparetic limb\textsuperscript{92,93}, where the reduced propulsive force of the paretic limb translates to smaller steps lengths of the nonparetic limb\textsuperscript{94}. While the deviations described are common in post-stroke gait, individuals may exhibit some or none of these deviations, due to interindividual differences.
2.3.3.1 Temporal Gait Asymmetry

Asymmetry is a prominent feature of post-stroke gait. Theoretically, asymmetry can be expressed using almost any bilateral variable of interest including kinematic variables (e.g. peak knee flexion angle of the paretic and nonparetic limbs), kinetic variables (e.g. GRF of the paretic and nonparetic limb during stance) and spatiotemporal variables (e.g. step length). Central to this thesis is temporal gait asymmetry (TGA).

Gait asymmetry has been described as a ‘compensation’ for the motor impairment that enables gait function. Compensation is considered the emergence of new motor patterns of end effectors (i.e., body parts such as the leg and foot) to carry out functions executed by different motor patterns previous to stroke. Motor impairment of the LE is associated with TGA, suggesting that at least in some cases it is a compensation adopted by the individual in order to have some walking function. However, motor impairment it does not explain all the variance observed in TGA post-stroke and there are examples of the presence of TGA in individuals with higher level of motor recovery. Thus, it is plausible that factors other than motor impairment contribute to the TGA and this may be particularly true in the specific case of asymmetrical walkers with milder motor impairment. For example, TGA may be directly caused by brain lesions that impair the ability to produce regular and rhythmic timing of gait events. Therefore, while TGA may be a compensation for motor impairment of the affected leg in some individuals, in others it may be a direct result of impairments to the systems involved in locomotor pattern generation. Therefore, for the purposes of this thesis, TGA will be referred to
as a g ‘deviation’, rather than a ‘compensation’, since TGA is a deviation from a typical gait pattern, that may be a result of compensation for impairment or of impairments directly.

Temporal asymmetry, the specific focus of this thesis, is characterized by unequal amounts of time spent in specific phases of gait (e.g. swing time, stance time) between right and left limbs. Temporal asymmetry can be quantified by ratios of the left and right limb values. There are also established cutoffs to determine whether a ratio value represents asymmetric gait as compared to healthy older adults\textsuperscript{98}. For example, a swing time ratio (larger value/smaller value) of greater than 1.06 is considered temporally asymmetric\textsuperscript{98}. Other common temporal deviations include greater stance time and SLS of the nonparetic limb, and increased overall DLS with terminal DLS of the paretic limb being greater\textsuperscript{74–77}. One potential explanation for this temporal asymmetry is motor impairment of the affected limb that leads to difficulty executing swing and, consequently, increased amount of time spent in the swing phase\textsuperscript{77,92}. Other studies have found that spasticity of the affected ankle plantarflextors is a primary determinant of TGA, suggesting that greater hip and knee flexor movements are used during the swing phase to accomplish foot clearance, consequently increasing the duration of swing of the paretic limb\textsuperscript{92,99}. Another possible factor causing temporal asymmetry is sensory impairment of the affected limb, which suggests that better sensation leads to increased confidence in landing the affected foot terminating swing phase, and therefore shorter swing phase of the affected limb, compared to those who have more severe sensory impairments\textsuperscript{92}.
2.3.3.2 Consequences of Temporal Gait Asymmetry

Temporal gait asymmetries can lead to secondary consequences that can impede mobility and decrease independence. One consequence may be musculoskeletal injury of the nonparetic lower limb. The high ground reaction forces repetitively applied through the unaffected limb has been positively correlated with TGA \(^{68}\). The nonparetic limb also spends more time in SLS and less time in swing than the paretic limb, consequently, more time is spent weightbearing on the nonparetic limb \(^{68,75,100}\). One possible explanation for this could be a reluctance to bear weight on the paretic limb, leading to the increased swing of the nonparetic limb and delayed initiation of foot contact, to reduce the amount of time spent on the paretic limb in SLS, subsequently, more time is spent in stance on the nonparetic limb than the paretic limb. This type of repetitive and prolonged loading associated with asymmetric gait has been linked to joint pain and degeneration. Findings in the unilateral amputee population, who also show asymmetrical gait by nature of their prosthetic limb, show that spending more time on the intact limb than the prosthetic limb subjects the intact limb to greater stress that may lead to joint pain and degeneration of the limb \(^{101,102}\). Improved gait symmetry may reduce repetitive loading in the unaffected limb, and decrease the risk of developing musculoskeletal injuries.

Temporal gait asymmetry also has repercussions for the affected limb. Decreased bone density, or osteoporosis, may occur after prolonged non-use of the affected limb\(^{103}\). Load bearing of the limb helps to maintain bone density and bone health. The reduced muscle activity and decreased weight bearing activity of the affected limb leads to loss of bone mineral density and increased risk of injury \(^{8,103–105}\) with the risk of hip/femoral neck fracture increasing
two fold after stroke. Reducing immobility of the affected limb and improving symmetrical weight-bearing during walking could reduce bone mineral density loss and reduce the risk of injury.

Increased energy expenditure, despite decreased capacity for ambulation, is another consequence of post-stroke gait asymmetry. A study examining the metabolic costs of walking in healthy individuals indicates that, compared to symmetrical walking, there is a substantial increase in energy costs when asymmetrical walking is induced using a dual-belt treadmill. Similarly, another study on energy expenditure during walking showed that, compared to healthy controls where gait is automatic, individuals with stroke had a higher oxygen uptake during walking and therefore a greater demand for energy during asymmetric gait. This discrepancy in energy expenditure indicates that the altered gait pattern as a result of a stroke compromises the efficiency of ambulation. Furthermore, a study in the amputee population with asymmetric gait showed that increased gait symmetry resulted in decreased energy demands. It is reasonable to apply this same concept to individuals with asymmetric gait due to stroke. To reduce energy inefficiencies due to TGA, new methods of improving gait symmetry are required.

Furthermore, post-stroke gait asymmetries are associated with challenges with dynamic balance control. Balance and gait deficits are linked to post-stroke falls and loss of balance while walking is reported as the most common activity when the fall occurred. Consequences of post-stroke falls can include reduced ambulation, increased sedentary behavior and decreased community participation. To decrease the risk of these secondary
consequences, gait rehabilitation focusing on improved symmetry requires more careful consideration.

2.3.3.3 Treatment of Gait Disorders Post-Stroke

Gait Training

Post-stroke rehabilitation has a large focus on gait training, with 25% to 45% of physical therapy time spent practicing gait, especially at the very beginning of rehabilitation\textsuperscript{117}. Common interventions used to improve walking ability post-stroke are Bobath framework, neurodevelopmental techniques (NDT), strength training, treadmill training, and intensive mobility training\textsuperscript{118}. The most commonly used measures of functional ambulation are self-selected walking speed and endurance, measured by the six minute walk test (6MWTo or similar test), therefore the effectiveness of many gait training programs are evaluated based on these measures. Bobath and the related yet separate NDT approaches are commonly used in stroke rehabilitation\textsuperscript{119–121} and while it does not show superior outcomes compared to other interventions\textsuperscript{122–124}, it has shown improvements in temporal gait parameters such as SLS time\textsuperscript{125}. Strength training of the lower extremity (LE) is proven to increase muscle strength of the limb, which has benefits such as improving bone mineral density, but does not have a direct effect on improved gait\textsuperscript{42,45,126}. A number of meta-analyses examining the effectiveness of treadmill training (with or without body weight support) largely agree that there is no significant difference in gait improvements when compared to or combined with other physiotherapy interventions (e.g. stretching, strengthening, overground gait training)\textsuperscript{118,127}. 
However, some studies of treadmill training in people with chronic stroke demonstrated increased gait velocity after training\textsuperscript{128,129}. Finally, there is evidence suggesting that intensive mobility training (which includes a combination of aerobic training, functional strength training and dynamic walking tasks) is a superior approach to improving endurance and walking speed post-stroke and has additional benefits of improving cardiorespiratory fitness, bone density, balance confidence and strength\textsuperscript{118,130–132}.

Common gait training practices, show some improvements in gait ability after stroke, though the target is often increased velocity and endurance\textsuperscript{123,133}. These interventions are largely ineffective at improving other temporal gait parameters, with the majority of asymmetric stroke patients showing no improvement in these measures during rehabilitation\textsuperscript{134,135}. Although some measures of functional ambulation improved with conventional rehabilitation strategies, given the potential long-term consequences of persistent temporal asymmetry, a greater focus should be placed on improving this particular post-stroke gait deviation.

**Interventions for TGA**

Conventional rehabilitation does not result in improved TGA\textsuperscript{136}, though some experimental interventions have shown promise for improving TGA. One such intervention is split belt treadmill training\textsuperscript{135,137–139}, where patients can practice walking with the belts at different speeds, to facilitate the movement of the paretic limb. While this treatment has shown to be effective for short-term improvement in spatiotemporal gait parameters (up to 3 months post-treatment)\textsuperscript{137}, the equipment is not readily accessible in clinical settings due to high costs\textsuperscript{140}. 
Rhythmic auditory stimulation (RAS) is another therapeutic approach that shows improvement in gait asymmetries is rhythmic auditory stimulation (RAS)\textsuperscript{123,141}. This treatment shows improved asymmetry in spatial characteristics like step length, velocity, as well as temporal variables such as swing time, although not to the same extent as spatial variables\textsuperscript{123,141}. For example, velocity and step length improved by 164% and 88%, respectively, while swing symmetry improved by 32% six weeks after RAS training. Although it is important to note that the control group, which received NDT/Bobath therapy, also showed 16% improvement in swing symmetry at six weeks\textsuperscript{123}. This finding highlights the view that temporal asymmetry can be changed, however interventions that specifically target this gait parameter may be required.

Advances in treatment of post-stroke asymmetrical gait are evident\textsuperscript{123,135}, however, they have limitations: feasibility in a clinical setting, lack of effectiveness for altering temporal characteristics, compared to spatial characteristics and, does not address underlying factors. New approaches that address these issues are necessary. One option for improving and creating new interventions for TGA is through the application of motor learning principles, specifically augmented feedback. Motor learning principles for individuals with stroke may differ from those established in healthy adults due to altered sensorimotor capabilities\textsuperscript{71}. Augmented feedback is currently used during rehabilitation, although parameters for its application (e.g. format and frequency) remain unclear. Optimized application of feedback principles during post-stroke gait training, targeted at improving TGA, may enhance gait outcomes and help reduce the risk of long-term negative consequences.
2.4 Motor Learning

Motor learning is defined as “a set of processes associated with practice or experience leading to relatively permanent changes in capability for skilled movement” \(^\text{142}\). Practice can be defined as repeated attempts to produce a movement that is outside an individual’s current capability\(^\text{143}\). During practice, processes and conditions are applied to the task and environment that alter the interaction the individual has with them, facilitating the search for task solution and leading to acquisition of a skilled action. The term skilled action has come to mean high levels of effectiveness and efficiency in movement, encompassing accuracy, consistency, reliability, and automatic economical execution of movement\(^\text{144}\). In healthy adults, practice conditions have been established that optimize acquisition and result in the relatively permanent ability to produce the skilled action\(^\text{142}\).

There are theories of motor learning to explain the mechanism of skill acquisition. Schmidt’s Schema Theory is based on closed loop motor control, in which sensory information about an ongoing movement is compared with the stored memory of the intended movement that is used as a reference to detect error and adjust movement accordingly\(^\text{63,145}\). However, this theory does not account for the production of novel movements or movements that occur in the absence of sensory feedback\(^\text{63}\). Newell’s Ecological Theory proposes that motor learning is based on a search for optimal strategies for task solution during practice, congruous with the environmental and task restraints. This search for a task solution is facilitated by complex perception/cognition/action processes resulting from the interaction between the individual with the task and environment\(^\text{63,146}\). Newell’s theory accounts for more factors that are
essential to motor learning, though it is still fairly new and yet to be systematically investigated relative to specific motor skill acquisition examples. Other theories explain skill acquisition with respect to the process of learning over time. Fitts and Posner propose a three-stage model for motor learning that focuses on the provision of cognitive resources and degree of attentional demand of producing a skilled movement. Initially the new task requires a high attentional focus as the task is investigated and various strategies are attempted to produce the skilled movement. This ‘cognitive stage’ results in high variability and large improvements in performance as an effective strategy for producing the movement is developed. Once the best movement strategy has been selected, the movement is refined for optimal performance, displaying less variability, smaller improvements and reduced attentional demand. The final stage of motor learning in this theory, the ‘autonomous stage’, requires a much lower degree of attention as the automaticity of the task increases. During this stage, more attention is diverted to external factors that may affect performance such as scanning the environment for features that could affect the task or performing another task simultaneously.

Another three-stage model originally proposed by Bernstein and adapted by Vereijken, Newell and colleagues, the systems theory, suggests that the central component of motor learning is the control of the degrees of freedom. The theory suggests that learning a motor skill begins with a reduction in the degrees of freedom to simplify the task and learn the general movement, called the ‘novice stage’. The ‘advanced stage’ follows in which more degrees of freedom are released, resulting in more precision and greater ability to respond to task and
environmental demands. In the third stage, the ‘expert stage’, all the degrees of freedom have been released, increasing the efficiency of execution under a variety of demands by modifying characteristics of the movement.

A two-stage model of motor skill acquisition has been proposed by Gentile\textsuperscript{150,151}, which describes the goals of the learner at each stage. During the first stage the learner’s goal is to understand the task, explore movement strategies and discern characteristics of the environment that could affect the task performance. During the second stage the learner’s primary goal is to refine the movement, including consistent and efficient task execution, as well as the ability to adapt movement to meet changing task and environmental demands.

Fitts and Posner’s model of motor learning stages is particularly suited for rehabilitation in patient populations as therapy begins early in recovery, which may be equated to the cognitive stage of the model. Employing the principles of motor learning that are ideally suited to this stage of the learning process may optimize rehabilitation outcomes. The use of augmented feedback during the cognitive stage, or early in rehabilitation, is a good illustration of such a principle\textsuperscript{152}. Frequent provision of feedback during the early stages aids the learner in understanding the task and creates a reference for correct movement patterns. As the learner approaches the autonomous stage, feedback should be more precise and less frequent so that skills can be refined without becoming dependent on the extrinsic source of information about their movement\textsuperscript{145,151}.
2.4.1 Motor Learning in Healthy Adults

Motor learning can be measured directly through neural activity during performance (e.g. electroencephalography\textsuperscript{153}, functional magnetic resonance imaging\textsuperscript{154}), but is often inferred from indirect measures of performance, such as movement outcome and movement characteristics. A common experimental paradigm used to evaluate the effectiveness of the application of various principles applied to practice is the use of a retention design, which includes an acquisition and retention phase\textsuperscript{142,155}. During the acquisition phase, the skill is practiced under specific conditions by manipulating one element of practice to varying degrees in two or more groups (e.g. control group and experimental group). After a set amount of time, where the skill is not directly practiced under the outlined conditions, the retention phase occurs. During retention, the skill is performed under the same conditions by both groups, and performance is measured. Motor learning is said to have occurred if there is improved performance during the retention phase. The group that performed better during retention would indicate the optimal condition to apply to practice that lead to more permanent ability to produce the skilled action.

Elements of practice can be manipulated to aid in the acquisition of a motor skill. These elements can include level of practice, practice design, and provision of feedback. Level of practice refers to the amount of practice, which could be measured in time or number of repetitions, where the amount of practice required is dependent on the stage of the learner\textsuperscript{63}. It has been shown that larger improvements are seen early on with lots of practice, then smaller increments of improvement are observed as there is less and less room for
improvement\textsuperscript{156,157}. The rate of improvement at any point of practice is linearly related (on a log scale) to the amount left to improve\textsuperscript{142}. Repetition of a skill within practice can be organized to be constant or variable, such that the same skill is practiced repeatedly or variations thereof, are practiced during a session\textsuperscript{142,145}. Variable practice leads to greater ability to perform the skill outside the range that it was practiced. This practice designs may seem to make the acquisition of a skill more challenging, but leads to better retention performance\textsuperscript{158,159}. When repetitions within practice are varied, they can be scheduled to optimize learning, by performing repetitions in blocked random order; this is a form of contextual interference\textsuperscript{142,160}. Using a blocked practice design (low contextual interference), repetitions of one variation of the skill to be learned are performed, before moving onto another variation, and so on. A random practice design (high contextual interference) entails variations of the skill randomly distributed throughout the practice session. Shea and Morgan\textsuperscript{161} discovered that high contextual interference leads to poor performance during practice, but leads to better performance during retention tests. Blocked practice design also leads to poor transfer of performance in novel contexts, whereas the same context dependency is not as evident when the skill is practiced with high contextual interference\textsuperscript{162–164}. Therefore, practice design that includes variations of the skill randomly distributed throughout practice leads to optimal performance in novel contexts when practice has concluded.

The manner in which the skill is practiced is also a contributing factor in motor skill acquisition. The skill may be practiced in its entirety, initiation to completion of the task, every repetition.
Conversely, a skill can be practiced in parts, wherein the skill is broken down into segments to be practiced individually, then combined\textsuperscript{142}. This is most effective when a task can be naturally divided into parts, such as reaching, grasping and drinking from a cup\textsuperscript{165,166}. Other tasks, where transition between segments is an integral part of its performance, are ideally practiced in whole rather than in parts\textsuperscript{167,168}. Gait is a prime example of such a task, in that a patient could practice bearing weight on a single limb to improve stance stability, however the shifting of weight from the opposite limb and weight acceptance before achieving SLS are integral to completing a gait cycle.

During training of a skill, instruction about the movement are often provided to guide the learner’s performance and can be delivered as explicit or implicit information\textsuperscript{142,160}. Where explicit instructions inform the learner of how to carry out the movement with rules and knowledge about the movement itself, implicit instructions do not declare such rules, allowing the learner to make discoveries about the movement outcome independently\textsuperscript{169}. In healthy learners, copious evidence supports that providing explicit information about the movement, requiring conscious awareness of performance, actually degrades learning\textsuperscript{169–171}. Conversely, implicit learning allows the learner to discover correct movement patterns and use sensory information to guide movement with less attentional demand, rather than focusing on specific movement goals which may hinder automatic control of movement\textsuperscript{172}. Similarly, attentional focus (internal versus external) is an aspect of practice that has a similar effect, where external foci (focus on movement outcome) is superior in facilitating skill acquisition, compared to internal foci (focus on body movements)\textsuperscript{173,174}. While there are numerous studies proposing that the optimal focus of attention is dependent on the stage of the learner\textsuperscript{173,175–177}, a review
by Wulf\textsuperscript{178}, provides strong evidence that external attentional focus is superior, regardless of learning stage\textsuperscript{179–181}. It may be surmised that similar to the effects of explicit knowledge, internal foci demand too much conscious awareness, interfering with the automaticity of the movement. Gallwey \& Kriegel\textsuperscript{182} provide a rather simplistic yet appropriate explanation for this effect: “doing rather than thinking about doing”.

**Feedback During Motor Learning**

Feedback during motor learning is generally classified into two types: intrinsic and extrinsic feedback\textsuperscript{142,160,183}. Intrinsic feedback, also called task-intrinsic feedback, refers to any source of information inherent to the movement and environment: visual, auditory, tactile and proprioception\textsuperscript{142,184}. Extrinsic, or augmented feedback, is often utilized during practice to enhance the learner’s intrinsic feedback and provide motivation to continue working toward the movement goal\textsuperscript{185–187}. The broad use of the term augmented feedback can be used to describe any source of information provided to the learner originating from an external source and will be referred to in the remainder of this section, as simply feedback. While feedback is not always necessary and can even hinder motor skill acquisition, it is often used to enhance motor learning\textsuperscript{160} presented in appropriate format (e.g. type, frequency, content, mode).

There are two main categories of feedback, knowledge of results (KR) and knowledge of performance (KP). KR is information about the outcome of the movement, whereas KP is information about the movement characteristics\textsuperscript{150}, both of which have advantages depending on the goal of the skill\textsuperscript{160}. As KR is a focus of this thesis, further discussion of feedback will be in
reference to KR. The content of KR can be information about correct aspects of performance or errors; which is superior is still largely debated and may be dependent upon the role of the feedback (e.g. direct external attention, provide motivation)\textsuperscript{160}. KR can take a variety of forms; for example, the information about the movement outcome can be qualitative (e.g. right/wrong, long/short), quantitative (e.g. numerically, graphical representation) or a combination thereof (e.g. error occurrence and the magnitude of error); the latter of which provides more guidance in how to correct the movement in future trials\textsuperscript{142}.

Feedback can be provided in differing amounts and various schedules, which can impact the effectiveness in improving performance and retention of a motor skill. Feedback can be provided in real time during the repetition (i.e., concurrent feedback), or it can be provided once the repetition is complete, called terminal feedback\textsuperscript{183}. There is a vast body of literature supporting the use of terminal feedback and its benefits. Concurrent feedback can be effective under certain learning conditions where intrinsic feedback is not always readily available; however, more often, concurrent feedback has a negative effect on learning. Concurrent feedback can give rise to dependency upon external information, such that practice performance improves, but retention of the skill when the feedback is no longer available is degraded\textsuperscript{188–190}. It is proposed that this is due to a ‘blocking’ effect that the augmented feedback has on the learner’s inherent feedback, whereby the skill is not truly learned, as determined by retained ability to perform at a later period. A similar effect is seen when evaluating frequency of feedback (e.g. how often the feedback is provided)\textsuperscript{191–193}. It is largely accepted that less than 100% feedback is best for skill retention\textsuperscript{183}. The same type of
dependency on external information and lack of retained skilled performance can be seen when feedback is provided after every trial.

It is clear that many variables of practice can be manipulated in order to optimize skill motor learning, such as schedule, type, organization and use of feedback. Generally speaking, in healthy adults, practice sessions that are variable with high contextual interference are ideal for skill retention and transferability\textsuperscript{161}. Whether repetitions of the task are practiced in parts, or as a whole, is dependent upon the nature of the task. To reduce constrained motor control and reduce attentional demand, implicit instruction and an external focus of attention should be used. Based on the literature reviewed, it is apparent that augmented feedback in the form of knowledge of results is beneficial for skill acquisition, with less feedback (<100%) showing better retention performance. The field of motor learning is vast and very well studied, although it remains unclear whether these same principles of practice can be effectively applied to neurological populations such as people with stroke.

2.4.2 Motor Learning in Adults with Stroke

The field of motor learning is concerned with the acquisition of movement skills, but can be defined in the context of recovery and rehabilitation as the reacquisition of movement skills\textsuperscript{63}. Rehabilitation is “fundamentally a process of relearning how to move”\textsuperscript{194}. Due to altered neurological structures and communication as a result of stroke, the principles of motor learning applied to neurotypical learners may not be the most effective approach for skill reacquisition in this population. In recent years, various aspects of practice (or therapy
sessions) during post-stroke motor re-learning have received increased attention\textsuperscript{19,195}. Many of these studies focus on motor tasks of the UE\textsuperscript{196–198}, rather than the LE\textsuperscript{199,200}, though some studies investigating motor learning principles applied to gait will be reviewed in this section.

Optimal scheduling of practice for people with chronic hemiparesis may not be congruent to that of healthy adults, in that variations of a task randomly distributed throughout practice may only improve some aspects of motor performance. A study by Hanlon\textsuperscript{201} compared the effects of random and blocked practice of a reach and grasp task among people with unilateral stroke. The random practice group completed 10 trials per session, where the primary task was alternated with three variations, creating high contextual interference. The blocked practice group performed 10 trials of the primary task in blocks of 5 trials (low contextual interference), with a five-minute rest between blocks. Unlike studies of practice schedule with neurotypical individuals, the practice type did not have an effect on task performance during acquisition. There was no difference in the number of trials required to meet success criterion (completion of the task three consecutive times), nor the time required to successfully complete the task; although the random practice group subjectively reported that it was more difficult to perform the task. At retention trials, the random practice group required fewer trials to meet criterion, however the blocked practice group improved in this respect from the first to second retention trial. Interestingly, time to complete successful trials was not different between the groups at retention trials. These finding suggest that random practice providing high contextual interference leads to superior retention of some aspects of performance (e.g. number of trials required to complete task) of an upper extremity task after stroke but not others (e.g. time to complete task).
Principles regarding type of task training (whole vs part) are consistent with those of neurotypical adults, in that training type is dependent on the task being trained. Motor learning principles developed from work with neurotypical adults has shown that part task training is ideal for tasks that can naturally be divided into parts\textsuperscript{166}, while whole task practice is better for tasks in which transition segments are imperative to the performance of the task\textsuperscript{168}. Hochstenbach and Mulder\textsuperscript{202} suggest that due to the motor, perceptual, cognitive and behavioral effects of stroke, total movement patterns are remembered better than isolated actions. There is limited evidence that part-task training aids in learning a serial task (e.g. sit to stand)\textsuperscript{203}, but is not as effective for learning a continuous task (e.g. walking)\textsuperscript{204}, suggesting that part/whole task training principles align with those developed in neurotypical adults. The influence of implicit and explicit information during motor learning is also consistent with that of healthy adults. Boyd and colleagues\textsuperscript{198,205} have done extensive work examining the effect of explicit information on implicit learning of a motor-sequence of finger tapping. They have confirmed that explicit information interferes with motor learning after stroke\textsuperscript{198} similar to neurotypical adults\textsuperscript{171}. Further, the magnitude of capacity for implicit learning is greater in those with mild strokes, compared to those with moderate strokes\textsuperscript{195}. It is again important to note that these studies used an upper extremity task. In regard to focus of attention during task performance, findings in the stroke population are again consistent with healthy adults, in that internal focus of attention is superior. Studies examining the effect of attention foci on an upper extremity task concluded that external focus of attention was superior\textsuperscript{206,207}, which was also found to be the case in a study evaluating the automaticity of a LE stepping task\textsuperscript{208}. 
Feedback

Augmented feedback during motor learning is important for individuals with neurologic injury like stroke, since intrinsic feedback may be limited due to disruption of neural networks\textsuperscript{71}. This means that intrinsic feedback about movement (e.g. proprioception and tactility) may be unreliable and/or may be interpreted incorrectly\textsuperscript{71}. Feedback is often provided during therapy sessions in the form of verbal, visual or manual guidance\textsuperscript{209}, however the content of which is usually motivational and reinforcing, rather than providing information about a movement\textsuperscript{19}. It has been suggested that both KR (knowledge of results) and KP (knowledge of performance) are effective for improving hemiparetic arm motor performance, although KP may have more lasting benefits and lead to better movement quality\textsuperscript{197,210,211}. The optimal mode of feedback remains unknown, however it is apparent that people with stroke are able to use a variety of feedback sources (e.g. visual\textsuperscript{212} or auditory\textsuperscript{211}). Very few studies have investigated optimal parameters for feedback scheduling after stroke and the evidence available is inconclusive. A study that used terminal visual feedback about an upper extremity timed tracing task at a frequency of 100\% or a relative frequency of 67\%, found that feedback condition did not affect accuracy or consistency of the task at retention when feedback was no longer provided\textsuperscript{212}. Similarly, a study using a grip force production task providing feedback about actual force production at either 100\% or 50\% frequencies, found no significant difference between groups at no feedback retention\textsuperscript{213}. It is apparent that there still remains a large gap in the literature regarding the provision of augmented feedback during the relearning of an upper extremity motor task.
While some principles for feedback of the upper extremity remain ambiguous, the provision of augmented feedback for LE motor tasks has received considerably less attention, especially a bilateral task that was previously automatic such as gait. Stanton and colleagues\textsuperscript{199} conducted a review examining the use of biofeedback (visual, auditory, tactile), and the effect it has on lower limb activities such as standing up, weight shifting and walking. Feedback provided included information about weight distribution between limbs, muscle activity, spatiotemporal gait parameters, and joint angles which was provided via visual, auditory or tactile mediums. They found that biofeedback had a moderate effect on these LE activities immediately after training, when compared with conventional therapy, suggesting that this type of feedback is superior to conventional therapist feedback (e.g. verbal/socio-affective feedback)\textsuperscript{199} in the short-term. However, the long-term effects of this intervention are unclear due to limited data and biofeedback is not commonly used in stroke rehabilitation\textsuperscript{214}. There is a scarcity of information about the use of terminal feedback of any kind during gait training. This is concerning since the interventions described above are not easily implemented in the clinical setting. Previous work by Patterson and colleagues indicates that concurrent visual feedback can result in immediate changes in TGA during treadmill training. The visual feedback provided was a symmetry plot that presented information about the individual’s TGA as a ratio of right over left stance time, where the goal was to move the symmetry plot into the target range in the center of the display. Four of six participants who received feedback improved their symmetry in response to this visual feedback. However, concurrent feedback typically requires special equipment that can measure movement while it is occurring and customized programs that can generate feedback based on measures in real time. Furthermore, while the use of
concurrent feedback has shown promise in improving some aspects of LE activities, it may also lead to dependency and the blocking effect described in healthy adults, limiting capacity for true learning to occur\textsuperscript{188}. Thus there is a need to investigate the effects of terminal augmented feedback for gait training.

2.5 Summary

With the incidence of stroke in Canada on the rise, and less than ideal stroke rehabilitation outcomes, it is important to investigate effective rehabilitation strategies. Better post-stroke rehabilitation outcomes will lead to decreased dependence and increased HRQoL. Persisting gait deviations, such a TGA, can affect mobility and can have long-term negative consequences like musculoskeletal injury, bone density loss, challenges with balance and inefficient energy expenditure. TGA often persists after conventional rehabilitation therapy, and current experimental interventions, which have shown some promise for improving TGA, are often not feasible in the clinical setting. Clearly new approaches for treating TGA are needed, one of which may be to incorporate the principles of motor learning in overground gait training. While motor learning is well studied, and principles are firmly established for skill acquisition in healthy adults, motor learning as it applies to individuals post-stroke is still being investigated. This is especially true for motor learning of a bilateral lower extremity task which was previously automatic, such as walking. The principles that could be applied to practice of a LE task to enhance skill acquisition remains largely unknown. Further knowledge of how these principles apply to motor learning of the LE after stroke can aid the design of gait training programs that effectively improve TGA.
2.6 Study Objectives

This study aims to investigate the use of visual feedback provided to individuals with stroke during an overground walking practice session to improve TGA at a retention session. The initial primary objective of this study was to investigate the effect of different frequencies of augmented visual feedback on temporal gait asymmetry. Based on preliminary data using the first visual feedback display it was determined that a second objective was necessary; to investigate the effect of different visual displays of augmented feedback on temporal gait asymmetry.
3 Study: Use of Visual Feedback to Improve Temporal Gait Asymmetry Post-Stroke

3.1 Introduction

Walking is frequently affected by stroke and improved walking function is a commonly stated rehabilitation goal\(^2\). Post-stroke gait features a number of spatiotemporal deviations including decreased velocity, increased double support time and asymmetries between the limbs\(^{74,98}\). Although some improvements are made with rehabilitation, gait is still considerably slower and more asymmetric at discharge compared to healthy older adults\(^6\).

One deviation in particular, temporal gait asymmetry (TGA) occurs in 55% of individuals with stroke and is described as spending unequal amounts of time on each leg during walking\(^6\). If left untreated, TGA may have long-term negative consequences such as challenges with balance control\(^{111}\), inefficient energy expenditure\(^{109}\), loss of bone mineral density in the paretic limb\(^{103}\), and risk of musculoskeletal injury in the nonparetic limb\(^{102}\). Unfortunately, TGA does not respond to conventional rehabilitation and there is some evidence that TGA may worsen over time\(^{5,98,100}\).

Some experimental interventions show promise for improving TGA, including split belt treadmill training\(^{215}\) and rhythmic auditory stimulation\(^{141}\). While improvements in TGA have been made with split belt treadmill training, this type of intervention is not always feasible in a clinical setting due to high equipment costs\(^{215}\). Rhythmic auditory stimulation has also shown therapeutic promise, although greater improvements are seen in other gait characteristics such
as step length and velocity compared to improvements in TGA\textsuperscript{141}. While these experimental interventions show some improvement in temporal symmetry, they are either not readily accessible in the clinical setting, or not as effective for improving TGA compared to spatial symmetry.

Overground gait training is commonly used in clinical practice and research\textsuperscript{216} and has the benefit of repeated practice under conditions that closely approximate normal walking, including terrain, sensory cues, weight bearing, and velocity closer to normal walking speed. Conventional overground gait training post-stroke improves velocity and endurance\textsuperscript{216,217}, but practical and effective overground gait training strategies are required to address temporal asymmetry in post-stroke gait.

One potential approach to improve the effectiveness of overground gait training for TGA is to apply concepts of motor learning, defined as the relatively permanent capability to produce a skilled movement as a result of practice or experience\textsuperscript{142}. In the context of post-stroke rehabilitation, motor recovery can be viewed as the process of relearning motor skills such as symmetrical gait\textsuperscript{194}. These parallels between motor recovery and motor (re)learning may facilitate improvement in walking function – especially in producing more symmetrical gait.

One motor learning principle of particular interest to post-stroke gait rehabilitation is augmented feedback, defined as any information that is not immediately available to the learner from the body’s own movement\textsuperscript{63}. Augmented feedback is of specific interest since sensorimotor impairments caused by stroke may impede the feedback inherent to the learner’s movement\textsuperscript{71}. The retention test is a common paradigm used to evaluate the effects of motor
learning concepts such as augmented feedback provided during practice of a motor task. At the retention test, the motor task that was practiced is evaluated after a period without practice and any improvements in performance are considered evidence of motor learning\textsuperscript{218}. Studies using such retention tests have demonstrated that augmented feedback can improve motor learning in healthy adults\textsuperscript{191,219}. Furthermore, feedback can be given to the learner during a practice session at different intervals but in general, less frequent feedback (e.g. feedback after every 3\textsuperscript{rd} attempt) is typically better for skill retention\textsuperscript{220}.

Some motor learning principles have been investigated for upper limb recovery post-stroke\textsuperscript{221} however, the optimal conditions for the delivery of augmented feedback particularly for the re-learning of a bilateral lower limb activity like symmetrical walking has not been examined. Therefore, the overall aim of this study is to investigate the use of visual feedback provided to individuals with stroke during an overground walking practice session to improve TGA at a retention session. The initial primary objective of this study was to investigate the effect of different frequencies of augmented visual feedback on temporal gait asymmetry. Based on preliminary data using the first visual feedback display it was determined that a second objective was necessary; to investigate the effect of different visual displays of augmented feedback on temporal gait asymmetry.
3.2 Methods

3.2.1 Design

This study used a cross-sectional observational design that employed an acquisition and retention protocol\textsuperscript{142} to test the effect of 2 different visual feedback displays providing information about the amount of time spent on each leg during walking and 3 frequencies of visual feedback on TGA. Participants were randomly allocated into one of three feedback frequencies: 100% feedback (after every trial), ~50% feedback (after every second trial), or 0% feedback. Participants assigned to feedback groups (i.e., 50% or 100%) received feedback in the form of Display A or Display B. Therefore, there were five feedback condition groups: no feedback, 50% Display A (50A), 100% Display A (100A), 50% Display B (50B) and 100% Display B (100B).

3.2.2 Participants

Individuals with first occurrence of stroke >6 months since onset who exhibited temporally asymmetric gait (swing ratio >1.06\textsuperscript{98}) were enrolled in this study. Participants were recruited from the local community and screened for eligibility prior to enrollment. All participants were over 18 years of age and able to ambulate independently with or without a walking aid. Exclusion criteria for participation were: visual neglect, inability to comprehend and/or follow multi step instructions, history of multiple strokes, other neurological or musculoskeletal conditions that affected gait. This study was approved by the University Health Network Research Ethics Board and all participants provided written informed consent.
3.2.3 Testing Protocol

Participants underwent a baseline assessment to characterize clinical presentation and gait. Following the baseline assessment, participants were randomly assigned to a feedback condition (NoFB, 50A, 100A, 50B, 100B). Participants then practiced the overground walking task during the acquisition session (up to 25 trials), and returned to complete the retention test (10 trials).

3.2.4 Baseline Measurements

Clinical measures were recorded to characterize type and severity of impairments. Motor impairment of the leg and foot was measured using the Chedoke-McMaster Stroke Assessment (CMSA), which has established validity and reliability\(^ {222} \). CMSA is measured using a 7-point scale with lower scores indicating more severe impairment. The National Institute of Health Stroke Scale (NIHSS) is a valid and reliable scale for measuring neurologic impairment, with higher scores indicating more severe impairment\(^ {223} \). Plantar cutaneous sensation was measured using a monofilament examination (Touch-Test Sensory Evaluator, North Coast Medical, Inc., Morgan Hill, CA) on the heel and base of the fifth metatarsal of both feet. The monofilament was pressed against the target area until the filament bent, then the participant was asked whether they could feel it. Sham trials were randomly included throughout the testing, in which the monofilament did not touch the foot, but the participant was asked if they could feel it. Cutaneous sensation was considered intact if the participant responded correctly to 2 out of 3 trials. This process was repeated for each monofilament of decreasing thickness, until the
participant was no longer able to correctly identify 2 out of 3 trials, marking the individual’s threshold for plantar cutaneous sensation. Each monofilament thickness was marked by a score, where a higher score (i.e., thicker monofilament) indicated a reduced cutaneous sensation. The Montreal Cognitive Assessment (MoCA) is a screening tool which covers eight cognitive domains\textsuperscript{224} and was used to characterize level of cognitive impairment. The MoCA is both sensitive and reliable for detecting mild cognitive impairment in stroke\textsuperscript{225}.

3.2.5 Gait measures

Spatiotemporal parameters of gait were measured using a pressure sensitive mat. The Zeno Walkway (ProtoKinetics, Havertown, PA, USA) is a 488 cm long and 61 cm wide mat with 18432 1.27 cm x 1.27 cm embedded sensors. The scan rate was 120 Hz. The pressure sensitive mat recorded footfall events, which were processed using PKMAS software to calculate spatiotemporal parameters. Similar technology, such as GAITRite, has been used to measure spatiotemporal parameters of gait among persons with stroke which demonstrates good test-retest reliability\textsuperscript{226,227}. Walking trials were 30 seconds of steady gait (i.e., constant mean velocity), which typically included 2-3 passes over the pressure sensitive mat, at the participant’s preferred gait velocity.

3.2.6 Overground walking training with feedback

Participants walked across the pressure sensitive mat during the training session, which recorded spatiotemporal parameters used to generate the feedback provided.
3.2.6.1 Acquisition Session

During the acquisition session participants practiced overground walking across the pressure sensitive mat in trials of 30 seconds. The goal was to complete 25 trials during the acquisition session but this was adjusted according to participant tolerance. Rest breaks were provided when necessary. During each trial, the pressure sensitive mat recorded footfall events that were used to generate feedback. Feedback was provided to the participant at the end of the 30 second walking trials in accordance with the assigned frequency of feedback.

3.2.6.2 Retention Session

Participants returned for the retention session 24 hours after the acquisition session. This session consisted of 10 30-second walking trials over the pressure sensitive mat. During this session, no feedback was provided to any participants and temporal gait parameters were recorded.

3.2.7 Visual Feedback about TGA

During the acquisition session, visual feedback was provided to participants on a tablet (Galaxy Tab E, Samsung, Suwon, South Korea) in one of two formats: Display A (Figure 3.1) or Display B (Figure 3.2). The visual feedback was displayed using Excel for Android (Microsoft, Redmond, WA, USA). Display A was generated using the right and left swing times (seconds) collected by the pressure sensitive mat on the previous walking trial. The swing time values were entered into an Excel spreadsheet with a formula that calculated the TGA ratio (equation here). This TGA ratio was then plotted in Excel using the scatter plot function which was then displayed to
the participant. Similarly, Display B was generated using the left and right swing times (percent of gait cycle) collected by the pressure sensitive mat on the previous trial. These values were entered into an Excel spreadsheet, which then generated a bar graph of the time spent on each limb and was displayed to the participant. The full script for the instructions are included in Appendix A but are briefly described in Figure 3.1 and Figure 3.2.
Figure 3.2 Display A - a visual analog scale with a marker (solid black line) indicating amount of time spent on one leg compared to the other during walking. The participant was instructed to move the marker closer to the center of the display, and into the target zone (shaded area), by spending more even amounts of time on each leg during the subsequent trials.

Figure 3.3 Display B - a bar graph with two bars: time spent on left side, time spent on right side. The participant was instructed to make the left and right bars even height by spending more even amounts of time on each leg during the subsequent trials.
3.2.8 Data Processing

PKMAS software was used to automatically identify footfalls and impressions made by walking aids on the pressure sensitive mat. Each pass on the mat was then edited manually to remove any partial footfalls. After this processing, PKMAS software automatically calculated spatiotemporal parameters. This processing was completed following the baseline clinical gait assessment and after each walking trial that required feedback during the acquisition session. After the retention session, all remaining trials were processed and calculated variables were exported to an excel file for further statistical analysis and to create individual motor learning curves. Swing time symmetry was calculated by dividing the right and left swing times (sec.), with the greater value as the numerator\textsuperscript{98}. Other variables of interest included step length, velocity, cadence, swing and stance time as percent of gait cycle and initial and terminal support as percent of gait cycle.

3.2.9 Data Analysis

Descriptive Statistical Analysis

Statistical analysis was carried out with R Project 3.4.1 software (Vienna, Austria)\textsuperscript{228} and Microsoft Excel 2016 software. Mean and standard deviation (SD) was generated for each feedback group for demographic variables and median and interquartile range (IQR) were generated for clinical variables (CMSA leg scores, MoCA scores, NIHSS, scores). One-way ANOVA and Kruskal-Wallis tests were used for normally and non-normally distributed variables,
respectively, to compare demographic and baseline variables between groups. An alpha level of 0.05 was used as the threshold for statistical significance for all analyses.

Motor learning Curves and Single Subject Analysis

A motor learning curve for each participant was produced by plotting the TGA (left y-axis) and velocity (right y-axis) of each trial (x-axis) during acquisition and retention sessions. Single subject analysis, specifically the 2 standard deviation band method, was used to determine TGA outcome at retention for each participant. The motor learning paradigm closely parallels the A-B-A single subject study design with a behaviour (in this case TGA) measured during a baseline period, and intervention period (acquisition) and then during withdrawal of the intervention (retention). The 2SD band method is appropriate for single subject analysis when baseline data is stable and therefore sensitive to variability across phases, with 2 consecutive data points outside 2SD indicating a significant change in performance across phases. The 2SD band method was selected for analysis in this study because baseline TGA was expected to be reasonably stable as participants had not yet received treatment, and the multiple measures at retention were suitable for assessing change. The mean and 2SD of baseline TGA, as measured during clinical assessment, was calculated and used to create a band to which TGA during each trial of the retention session was compared. If the majority of retention trials (i.e. ≥6/10) had a TGA below 2 SD from the baseline TGA, the individual was classified as exhibiting a significant change in TGA. Participants that had <6 retention trials below 2SD band were categorized as ‘no change’.
Comparison of Spatiotemporal Gait Parameters at Baseline and Retention

In order to determine what aspects of gait changed to accomplish greater symmetry, paired t-tests were used to look for differences in gait parameters between baseline and retention in participants that were classified as having ‘changed’ symmetry. Measures of interest in this study were swing time (% of gait cycle), stance time (% of gait cycle), initial double support time (% of gait cycle), terminal double support time (% of gait cycle), step length (cm), of the paretic and nonparetic limbs, along with cadence (steps/min) and velocity (m/s). These spatiotemporal variables commonly deviate from normative values in asymmetrical post-stroke gait\textsuperscript{6,232}, and were therefore of interest to determine how they change in order to achieve improved TGA. These parameters were used in previous work to investigate change in gait symmetry within an individual and indicated that some of these parameters changed as symmetry improved with increased walking speed\textsuperscript{233}.

Effect Size

Effect size (Cohen’s $d$) was calculated to determine the effectiveness of each feedback condition (50A, 100A, 50B, 100B) compared to the control group based on mean change in TGA from baseline to retention.
3.3 Results

Participants

Sixteen participants (5 females, 11 males) with a mean (SD) age of 65.2(6.6) years, who were 6.2(5.4) years post-stroke participated. All participants exhibited TGA at clinical assessment with a mean TGA ratio of 1.32 (0.17) and performed walking trials using a walking aid as required (8 participants used an aid). Demographic data for individual participants and group means are presented in Table 1. The groups were not statistically significantly different on age (F(4,15) = 0.13, p = 0.97), time post-stroke (H(4,15) = 4.93, p = 0.29), CMSA score of the leg (H(4,15) = 2.78, p = 0.60), MoCA (F(4,15) = 0.13, p = 0.97), NIHSS score (H(4,15) = 1.55, p = 0.82), velocity (F(4,15) = 0.86, p = 0.52).
<table>
<thead>
<tr>
<th>Group</th>
<th>Participant ID</th>
<th>Baseline</th>
<th>TGA (years)</th>
<th>Age (years)</th>
<th>Sex (M/F)</th>
<th>Time Post-Stroke (years)</th>
<th>CMSA (leg)</th>
<th>MoCA</th>
<th>NIHSS</th>
<th>Gait velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n=4)</td>
<td>1</td>
<td>1.47</td>
<td>75</td>
<td>M</td>
<td>3.9</td>
<td>6</td>
<td>27</td>
<td>0</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.32</td>
<td>60</td>
<td>M</td>
<td>2.9</td>
<td>5</td>
<td>20</td>
<td>3</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.24</td>
<td>56</td>
<td>M</td>
<td>5.3</td>
<td>7</td>
<td>29</td>
<td>1</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.39</td>
<td>61</td>
<td>M</td>
<td>2.2</td>
<td>5</td>
<td>28</td>
<td>2</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Group mean (sd)</td>
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<td>1.36(0.1)</td>
<td>63.0(8.3)</td>
<td>3.6(1.3)</td>
<td>5.5(1.8)</td>
<td>27.5(7.0)</td>
<td>1.5(2.5)</td>
<td>0.90(0.1)</td>
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<td></td>
</tr>
<tr>
<td>50A (n=2)</td>
<td>5</td>
<td>1.45</td>
<td>83</td>
<td>M</td>
<td>6.7</td>
<td>4</td>
<td>28</td>
<td>0</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.25</td>
<td>66</td>
<td>M</td>
<td>2.6</td>
<td>5</td>
<td>25</td>
<td>2</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Group mean (sd)</td>
<td></td>
<td>1.35(0.1)</td>
<td>74.5(12.02)</td>
<td>4.6(2.9)</td>
<td>4.5(1.0)</td>
<td>26.5(3.0)</td>
<td>1.0(2.0)</td>
<td>0.77(0.2)</td>
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<td></td>
</tr>
<tr>
<td>100A (n=4)</td>
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<td>44</td>
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<td>6</td>
<td>30</td>
<td>1</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.12</td>
<td>60</td>
<td>M</td>
<td>1.6</td>
<td>6</td>
<td>28</td>
<td>1</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1.15</td>
<td>81</td>
<td>F</td>
<td>8.7</td>
<td>6</td>
<td>20</td>
<td>1</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.70</td>
<td>59</td>
<td>M</td>
<td>5.2</td>
<td>2</td>
<td>23</td>
<td>8</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Group mean (sd)</td>
<td></td>
<td>1.31(0.3)</td>
<td>61(7.0)</td>
<td>5.5(3.0)</td>
<td>6.0(3.0)</td>
<td>25.5(8.8)</td>
<td>1.0(5.3)</td>
<td>0.74(0.2)</td>
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<td></td>
</tr>
<tr>
<td>50B (n=3)</td>
<td>11</td>
<td>1.17</td>
<td>69</td>
<td>M</td>
<td>1.5</td>
<td>5</td>
<td>27</td>
<td>1</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1.24</td>
<td>58</td>
<td>M</td>
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<td>6</td>
<td>27</td>
<td>2</td>
<td>0.84</td>
<td></td>
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<tr>
<td></td>
<td>13</td>
<td>1.34</td>
<td>56</td>
<td>F</td>
<td>4.5</td>
<td>4</td>
<td>25</td>
<td>4</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Group mean (sd)</td>
<td></td>
<td>1.25(0.1)</td>
<td>61(7.0)</td>
<td>2.2(2.0)</td>
<td>5.0(2.0)</td>
<td>27(2.0)</td>
<td>2.0(3.0)</td>
<td>0.81(0.1)</td>
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<td></td>
</tr>
<tr>
<td>100B (n=3)</td>
<td>14</td>
<td>1.62</td>
<td>68</td>
<td>F</td>
<td>23.9</td>
<td>6</td>
<td>29</td>
<td>2</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.28</td>
<td>68</td>
<td>M</td>
<td>2.4</td>
<td>5</td>
<td>22</td>
<td>4</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1.09</td>
<td>64</td>
<td>F</td>
<td>21.0</td>
<td>5</td>
<td>23</td>
<td>1</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Group mean (sd)</td>
<td></td>
<td>1.33(0.3)</td>
<td>66.7(1.9)</td>
<td>15.8(11.7)</td>
<td>5.3(0.6)</td>
<td>24.5(3.8)</td>
<td>2.3(1.6)</td>
<td>0.83(0.08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample Mean (sd)</td>
<td></td>
<td>1.32(0.1)</td>
<td>64.2(6.6)</td>
<td>6.2(5.44)</td>
<td>5.0(1.0)</td>
<td>27.0(5.0)</td>
<td>1.5(1.8)</td>
<td>0.81(0.1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Motor Learning Curves and Single Subject Analysis

Figures 3.3-1 to 3.3-16 represent performance and retention of each participant. Half of participants that received feedback (6/12) during practice showed improved symmetry at retention. Severity of TGA was categorized as mild-moderate (≤1.5) or severe (>1.5), based on a similar categorization used in a previous study examining TGA\textsuperscript{6}. Fourteen participants had mild temporal asymmetry, and two had severe asymmetry. Of those that showed improved TGA at retention 4 had mild-moderate asymmetry and 2 had severe asymmetry.
Figure 3.4 Single subject analysis of TGA ratio (black line + circle marker), compared to 2SD (shaded band) of baseline asymmetry (white dashed line within shaded band), and velocity (m/s) (grey lines + square marker) across trials for acquisition and 24 hour retention session. Participants 1-4 did not receive feedback and participants 5-16 received feedback.
Participants classified as ‘change’ (i.e., exhibiting improved symmetry at retention) and ‘no change’ with the 2SD band method are summarized in Table 3.2.

<table>
<thead>
<tr>
<th>Group</th>
<th>Change</th>
<th>No Change</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
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<td>4</td>
<td>4</td>
</tr>
<tr>
<td>50A</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>100A</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>50B</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>100B</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>10</td>
<td>16</td>
</tr>
</tbody>
</table>

Comparison of Spatiotemporal Parameters of Baseline Gait to Retention Gait

Mean values for spatiotemporal parameters of participants who showed change in symmetry (i.e., improved TGA) at retention (n=6) are summarized in Table 3.3. Paired t-test of each parameter (baseline-retention) indicated that the ‘change’ group exhibited significant changes in swing time of the nonparetic limbs ($t(5)=-3.99, p=0.010$) and stance time nonparetic limbs ($t(5)=3.99, p=0.010$).
Table 3.3 Spatiotemporal parameters of individuals who showed change in TGA at retention gait (n=6)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Baseline</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/sec.)</td>
<td>0.51 (0.16)</td>
<td>0.52 (0.1)</td>
</tr>
<tr>
<td>Cadence (steps/min.)</td>
<td>77.1 (12.9)</td>
<td>75.9 (11.2)</td>
</tr>
</tbody>
</table>

**Paretic Limb**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Baseline</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Time (%)</td>
<td>31.9 (4.9)</td>
<td>31.5 (4.0)</td>
</tr>
<tr>
<td>Stance Time (%)</td>
<td>68.1 (4.9)</td>
<td>68.5 (4.0)</td>
</tr>
<tr>
<td>Initial Double Support Time (%)</td>
<td>18.6 (5.0)</td>
<td>17.5 (4.3)</td>
</tr>
<tr>
<td>Terminal Double Support Time (%)</td>
<td>25.1 (5.9)</td>
<td>24.1 (6.7)</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>39.2 (9.0)</td>
<td>40.3 (6.4)</td>
</tr>
</tbody>
</table>

**Nonparetic Limb**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Baseline</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Time (%)*</td>
<td>23.8 (5.6)</td>
<td>26.8 (6.1)</td>
</tr>
<tr>
<td>Stance Time (%)*</td>
<td>76.2 (5.6)</td>
<td>73.2 (6.1)</td>
</tr>
<tr>
<td>Initial Double Support Time (%)</td>
<td>25.3 (6.1)</td>
<td>24.0 (6.7)</td>
</tr>
<tr>
<td>Terminal Double Support Time (%)</td>
<td>18.7 (4.9)</td>
<td>17.5 (4.3)</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>40.1 (9.1)</td>
<td>42.6 (7.5)</td>
</tr>
</tbody>
</table>

Note. Values are mean (SD)
* p = < .05
Effect Size

All FB conditions had at least one participant demonstrate a change in TGA at retention. However, Cohen’s $d$ values for Display B were larger compared to Display A for both 50% and 100% feedback frequencies. Feedback condition 100B had the largest effect size and a mean difference of change in TGA at least twice as large as all other feedback conditions.

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean Difference</th>
<th>Pooled SD</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>50A (n=2)</td>
<td>0.05</td>
<td>0.09</td>
<td>0.54</td>
</tr>
<tr>
<td>100A (n=4)</td>
<td>-0.04</td>
<td>0.11</td>
<td>-0.37</td>
</tr>
<tr>
<td>50B (n=3)</td>
<td>0.07</td>
<td>0.08</td>
<td>0.86</td>
</tr>
<tr>
<td>100B (n=3)</td>
<td>0.14</td>
<td>0.12</td>
<td>1.23</td>
</tr>
</tbody>
</table>

3.4 Discussion

Providing augmented feedback during a single session of overground walking can significantly change TGA in some individuals with post-stroke TGA. In contrast, participants who performed overground walking with no feedback exhibited no improvement in TGA. With respect to feedback display and frequency, both displays and frequencies induced change in TGA in at least one participant and 3 out of 4 display-frequency combinations had at least a moderate effect size (e.g. $d$>0.5). However, Display B with 100% feedback was associated with a change in TGA in 100% of participants that received it and it also had the largest effect size of all the feedback display-frequency combinations. Thus, the effect of augmented feedback on TGA may
be influenced by the format in which information about TGA is presented and the frequency at which it is given.

Both frequencies of feedback for Display B had a large effect on the change in TGA compared to those in the control group. Display A had a moderate effect on TGA when feedback was provided for 50% of trials. Meanwhile, receiving Display A for 100% of trials had a small negative effect, wherein mean change in TGA for the group was worse compared to the control group. It is suspected that Display A was misinterpreted by participants and therefore did not have a great effect on TGA. During the acquisition session multiple participants verbalized finding Display A difficult to understand. Other participants described the way they were interpreting the feedback at some point during or after the acquisition session, which was different from its intended meaning. In these cases participants’ statements indicated their interpretation of feedback as indicating their position spatially on the mat (i.e., walking in the middle of the mat versus to one side or the other) rather that the intended meaning which was the temporal symmetry pattern. For example, one participant said, “I was trying to walk closer to the middle of the mat, to move the line on the display”. This was somewhat surprising since previous work by Patterson used a similar visual display during a single treadmill training session which was associated with reduced temporal asymmetry and no such misinterpretation was observed. However, in this case the feedback was provided concurrently which may have facilitated the correct interpretation of feedback display. In previous post-stroke motor learning studies, a variety of visual information is presented as augmented feedback, however a study by Sackley and Lincoln used a display similar to Display B of the current study, to evaluate its effect on weight bearing symmetry during quiet standing. Two vertical bars represented
the weight distribution of each limb on force plates, moving up and down in accordance with weight bearing of the left and right side, where the goal was to bring the bars within 5% of each other. While this visual feedback intervention resulted in improved weight bearing symmetry and reduced postural sway, the feedback was concurrent, and the population was individuals with subacute stroke\textsuperscript{234}. The design of visual displays has not been well studied, although abstract visualizations such as the plots used to design Display A (target area/shaded band) and Display B (bars representing distribution) has proven to be effective for motor learning in healthy adults and individuals with stroke\textsuperscript{220,234,235}. Future work could investigate visual feedback design factors that enhance interpretation and hence effectiveness of visual feedback, as the current state of the knowledge is very limited.

Previous work on the use of visual feedback for motor learning in healthy adults suggests that the stage of the learner and the complexity of the task dictate the frequency at which feedback should be provided. In the early phases of learning, frequent feedback aids the learner in understanding the task and exploring movement patterns\textsuperscript{145,193}. It is also suggested that frequent feedback is optimal for the learning of complex motor tasks\textsuperscript{236}. It is possible that the 100% frequency schedule resulted in more participants with changed TGA, compared to those that received feedback at 50% frequency, due to the learning stage of the participants and the nature of the task. Participants were in the early stages of learning the novel bilateral coordination task and therefore more frequent feedback may have facilitated the search for a movement pattern that resulted in greater symmetry more successfully than those who received less feedback.
It is important to note that TGA with visual feedback did not appear to be accompanied by a change in velocity at retention. This is positive since it implies that altering one component of the gait pattern (i.e. temporal symmetry) does not necessarily result in a negative trade-off on other aspects of gait (i.e. forward progression). Furthermore, reduced TGA at retention seemed to be achieved by an increase in nonparetic swing time indicating that participants spent more time in SLS of the paretic limb in order to make time spent on each limb more equal. This is an encouraging outcome since the intended effect of the feedback was to improve TGA through increased use of the paretic limb which was recommended by previous work on the use of feedback to improve TGA\textsuperscript{220}. Increased time spent in SLS on the paretic limb is likely associated with increased weight bearing which is beneficial for maintaining bone mineral density and reducing risk of hip fracture after stroke\textsuperscript{103}. Similarly, decreased overall stance time of the nonparetic limb means reduced weight bearing on the nonparetic limb which lessens the impact that repetitive and prolonged loading can have on the joints and reduce the risk of musculoskeletal injury\textsuperscript{102}. Improved symmetry of swing and stance time of the nonparetic limb may also lead to more efficient energy expenditure\textsuperscript{109}. The impact of continued overground gait training with visual feedback on TGA and these secondary negative consequences are important issues to investigate further.

Improved symmetry was not associated with velocity or severity of TGA at baseline. One limitation of the 2SD band method is that the threshold used to judge change in TGA is not the same across individuals. Those with greater variability (i.e. larger SD) at baseline had a much larger 2SD band to which TGA at retention was compared to those with less variability at
baseline. The range of SD for the participants that were classified as change in TGA was 0.01 – 0.07 whereas the SD range for the group that did not change in TGA was 0.02 – 0.09.

### 3.5 Conclusion

The main finding of this study is that TGA changes significantly in some individuals post-stroke after receiving a single session of overground walking with augmented visual feedback. However, the effect may be influenced by the format in which the FB is provided. It also appears that both 50% and 100% FB results in improved TGA at retention but 100% has a bigger effect size. Results from this study, will inform longer-term TGA gait training studies, using display format B and providing feedback for 100% of trials. An overground gait training program that improves post-stroke TGA may reduce the risk of long-term negative consequences associated with TGA, increase mobility, decrease dependence and improve HRQoL.
4 General Discussion

Conventional gait training improves some aspects of post-stroke gait such as velocity and endurance\textsuperscript{123}, however, more effective interventions for treating post-stroke gait asymmetry are required. Previous work has shown improvement in spatial variables with experimental interventions, but do not improve temporal asymmetry to the same extent\textsuperscript{141,215}. As TGA can lead to long-term negative consequences\textsuperscript{68,103,109}, it is important that effective interventions that target TGA are developed. The current work investigates one such approach, using augmented feedback and the principles of motor learning to improve TGA.

Responsiveness of TGA to intervention

Temporally asymmetric gait has been considered resistant to intervention\textsuperscript{237}, and some consider it a neuromuscular compensation necessary for optimizing walking function\textsuperscript{238}. However, the current work demonstrates that changes can be made to temporal parameters of asymmetric gait after just one practice session and that these changes do not compromise other functional measures of gait such as velocity. All participants included in the study were in the chronic stage of stroke recovery, when improvements in walking are said to be limited\textsuperscript{3}, and yet half of participants who received feedback retained changes to their walking pattern 24 hours later in response to the feedback provided. The findings of this study suggest that more temporally symmetric gait can be achieved in chronic stroke in response to interventions targeted at changing temporal gait parameters and does not compromise other features of gait considered important for functional ambulation.
It is possible that responsiveness of TGA to visual feedback was impacted by individual underlying sensorimotor and cognitive impairments. Although there were no differences in CMSA, NIHSS, MoCA and plantar cutaneous scores between groups, the individualized nature of impairments among people with stroke causes no surprise that individuals of varying degrees of motor function and neurologic impairment were able to change TGA in response to the feedback. It is reasonable to surmise that those with greater somatosensory impairment would receive less reliable intrinsic feedback during practice about the result of the movement, and more challenges in executing the movement. Nonetheless, there appears to be no trend in severity of impairment and responsiveness of TGA to visual feedback. Cognitive impairment has also been linked to degraded motor control and learning, yet the median MoCA scores of those who had changed symmetry (median (IQR), 25.5(5.5)) at retention is remarkably similar to those that did not respond to feedback (26(4.8)). However, the range of the level of impairments is limited due to the small sample size and a future study with a larger sample size may better detect the effect of different impairments on the use of visual feedback to improve TGA in people with stroke.

Another potential factor that may impact responsiveness of TGA to feedback is lesion location. Lesion location was self-reported by 8 participants to the best of their knowledge (3 basal ganglia, central sulcus, internal capsule, pons, frontal lobe, middle cerebral artery, posterior base) and was unknown for the other 8 participants. It is long known that the cerebellum plays important roles in motor control and learning. There is evidence from fMRI studies of sequential motor skills that the cerebellum is particularly active during the early phase of
learning\textsuperscript{240}, when the movement is explored and adapted\textsuperscript{147}. A lesion to the cerebellum could impede motor relearning and interfere with the coordination of movement. It is possible that a lack of responsiveness to the intervention, especially during the early stages of relearning the task, is due to injury to the cerebellum. However, no participants in the sample reported lesion to the cerebellum. Another lesion site that may impede relearning of temporally symmetric gait, is the putamen. There is evidence that damage to the putamen is associated with the presence of TGA in the chronic stage\textsuperscript{241}. A lesion to this location may cause TGA to be particularly resistant to interventions, at least over one practice session. Interestingly, 3 of the 6 participants who did not respond to feedback, reported basal ganglia as lesion location. However, imaging studies of brain activation patterns during motor tasks indicate that, despite injury to these areas, motor learning is possible through recruitment of secondary motor areas such as supplementary and premotor areas\textsuperscript{242,243}.

Display Format

The current work demonstrated that augmented feedback in the form of visual information about temporal asymmetry can improve TGA after one overground practice session. The study specifically investigated the effectiveness of different visual displays and the optimal frequency at which it should be provided during practice. The results suggest that the format the information is presented in may play a role in its effectiveness. Both displays presented information about the amount of time spent on one leg compared to the other during a 30 second walking trial, but Display B resulted in twice as many participants exhibiting changed TGA at the retention session compared to Display A. It seems likely that this is due, at least in
part, to misinterpretation of the information presented in Display A by some participants, and statements to that effect were made by multiple participants. They expressed directly, or implied through various comments that they were using the information presented in Display A to adjust where they were walking on the mat (e.g. closer to the middle of the mat), rather than adjusting the time spent on each leg during the trial. This is despite repeated verbal instructions about how to interpret the display with respect to timing of events in the gait cycle. It is possible that participants perceived Display A to be a literal representation of the mat, with the red band indicating where on the mat they were aiming to walk and the black line representing their actual location on the mat. Participants viewed the feedback while standing or sitting at the end of the mat looking down the length of it, which may have also contributed to Display A being perceived as a representation of the width of the mat. Furthermore, the goal of the task was to move the marker across the display, which is inherently a spatial task, and perhaps another possible reason for misinterpretation of the information provided in Display A.

Meanwhile, Display B seemed to be more intuitive and participants expressed no uncertainty about the meaning of the information presented. It is possible that Display B was more easily understood since each bar was a direct measure of time was spent on each leg, and it was more apparent which one was larger. It may be assumed that those that improved TGA, understood that the display was presenting temporal information about their walking, since improved TGA was achieved by decreasing stance time of the nonparetic limb; the intended effect of the feedback.
Feedback Frequency

One visual display appeared more effective than the other, and the same is true of the frequency at which it was provided, again with double the amount of participants showing improved TGA receiving feedback after every trial (100%), opposed to receiving feedback after every other trial (~50%). In addition, Display B given at 100% frequency also had the largest effect size. This is opposite to feedback frequency principles established for healthy adults where too much feedback can degrade motor learning\textsuperscript{191}, although the larger amount of feedback may be more beneficial for people with stroke since it supplements intrinsic feedback that may be otherwise compromised\textsuperscript{71}. It is also possible that the greater need for feedback is only present in the early stages in learning the task, then, similar to healthy adults, less feedback may be recommended as the learner has a good understanding of the task and the new focus is to refine the movement pattern\textsuperscript{147}. Future work examining the effect of feedback frequency in different stages of relearning could optimize gait outcomes after stroke.

Implications for Rehabilitation

This type of intervention using augmented feedback shows promise for gait training targeting temporal asymmetry in people with chronic stroke, although it is not necessarily feasible in a clinical setting at this stage largely due to equipment costs. Some pieces of equipment used, such as a tablet and laptop, are often common-place in clinics, although the pressure sensitive mat used to record spatiotemporal gait parameters used to generate the feedback is quite costly. Many clinics may not have funds to support this type of equipment, although they are
being adopted in some settings associated with large research and teaching hospitals in large urban settings. An alternative method for recording spatiotemporal gait parameters that is more cost effective (e.g. accelerometers/tablet application), could make this type of intervention feasible for implementing in therapy.

However, some findings from the current work may be relevant to clinical practice once tested further in a larger clinical trial, such as the frequency of feedback to provide during gait training after stroke. The results from this work suggest that more feedback (e.g. 100%) during the early stages of relearning a task may better facilitate the process, specifically in gait training for temporal gait asymmetry. Therapists using feedback (e.g. visual or verbal feedback) during gait training targeting temporal asymmetry, may better facilitate the learning process by providing feedback after every repetition. This study indicates that one practice session leads to short-term retention of changes to symmetry, however, future work could investigate the impact of more practice sessions and longer follow up periods to determine the long-term retention of these changes. Furthermore, this study evidenced that interpretation of feedback can change from learner to learner and may not be interpreted by the learner in the intended way. It is suggested that therapists confirm that patients understand and interpret the information represented in the visual display in the intended way. Providing concise instructions that outline the visual information may have a large impact on whether the feedback is effective during therapy. Further work investigating the interpretation and comparison of visual displays could inform the design a display that effectively conveys visual information for relearning a walking task in people with chronic stroke.
4.1 Limitations

One limitation of this study is the small sample size and uneven groups sizes, leading to poor generalizability. Part of the challenge in enrolling participants, was finding participants who fit the inclusion criteria, especially temporally asymmetric gait. Twenty-four people with a first occurrence of stroke were screened, of which seventeen people exhibited temporally asymmetric gait. One participant with TGA was unable to complete the study due to the time sensitive nature of the study visits; acquisition and retention sessions required travel to Toronto Rehabilitation Institute on two consecutive days. Many other potential participants were contacted, but declined participation; indicating that they would be unable to meet the specific time demands of the study visits. Small group sizes were due to a protocol change in which Display B was added as a feedback condition, when it became evident that Display A was ineffective, likely due to misinterpretation of the information presented. Although the statistical analysis lacks power, single subject analysis enables conclusions about the effects of a condition based on the response of a single participant to be drawn. Analysis by group in this type of size sample is also made possible by the effect size calculation, that takes into account the small sample size. It is important to note that the small sample size of the current study limits the conclusions that can be drawn. The findings from this study will inform the next of several steps towards an eventual large clinical trial study. The next step is to test Display B provided at 100% frequency compared to a control group receiving no feedback, to support the format and frequency of visual feedback that should be used to improve post-stroke TGA.
Another limitation of the study is the baseline TGA measure that was used to determine change in symmetry at retention. Many participants showed great variability of TGA during the 30 second walking trial, which is common in post-stroke gait\textsuperscript{244}. However, this variability created different standards for improvement for each individual using the 2SD band method. Since improved TGA was defined by the majority of retention trials having a TGA ratio less than 2SD of baseline, those that showed more variation at baseline were required to improve by a larger margin. Meanwhile, it would be more likely for those that showed little variation at baseline, to improve TGA. Currently, there is no criteria for selecting the most appropriate analysis method for single subject research designs\textsuperscript{230}. However, the 2SD band method was used in this work because it assumes stable baseline data (i.e., TGA prior to intervention), is sensitive to changes across phases (i.e., baseline, acquisition, retention) and the multiple measures at retention lent itself well to assessing change (i.e., ≥6 trials below 2SD).

The retention test paradigm used in this study consisted of one practice session (25 trials) and one retention session (10 trials) 24 hours later. Many post-stroke motor learning studies employ a similar protocol of one acquisition and one retention session\textsuperscript{180,212}, however multiple practice sessions are also common\textsuperscript{245,246} and are closer to the reality of clinical practice in stroke rehabilitation. The use of one practice session may be seen as a limitation, though there is evidence that one overground gait training session can induce short-term changes to spatiotemporal parameters in people with stroke\textsuperscript{247}. The shorter testing protocol used in the current study showed changes in TGA over a single session and allowed for proof of concept to inform a larger gait training study. This suggests that further training using these methods could lead to greater changes in TGA.
4.2 Future directions

The findings from the current work demonstrate that visual FB can lead to improvements in TGA after one training session and provides insight for the development of future gait training programs. A larger randomized controlled trial using Display B to provide visual information about TGA at a frequency of 100% is recommended to investigate the optimal frequency at which FB should be provided. A future clinical trial should be designed with frequency and intensity of training comparable to that used in other studies on gait rehabilitation with chronic stroke, with multiple follow up sessions. For example, training may take place over a 4 week period, 2-3 session per week, each session consisting of 25 trials with follow-ups at 1 and 3 months post training. Follow-up will aid in determining longer-term retention of improvements to TGA following gait training with visual FB. A gait training program for improving TGA that employs the principles of motor learning, as they apply to individuals with stroke, may help reduce long-term negative consequences, decrease dependence and increase HRQoL.
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Appendix A

General Instructions for Acquisition Session

Today you will be performing a series walking tasks. You will be asked to walk across the grey mat on the floor, turn around at the marker on other side and walk back across the mat, if time permits. You will be asked to perform this task in blocks of 30 seconds, up to 25 trials. You will have a rest after each trial. Does this sound okay to you?

Display A

After every trial (for 100% condition, or every other trial for 50% condition), a tablet will be shown to you which will show you the amount of time you spend on each leg when you were walking. For example, if you spend equal amounts of time on both legs, then the marker will be displayed in the center. If you spend more time on your right leg while walking, then the marker will be on the right side of the screen. The more time you spent on the right leg the further to the right the marker will be. If you spend only slightly more time on your right leg then the marker will be closer to the center. The same is true for the left side.

This red band is the target area for your walking. A marker inside this area indicates an improvement in your walking pattern, compared to when we first began. So after you get the feedback, your goal is to try to walk so that the marker moves into the red band which is the target area. The closer the marker is to the center of the display, the better. Would you mind explaining it to me in your own words to make sure that we both understand?
Display B

After each trial, a tablet will be shown to you which will show you the amount of time you spent on each leg while you were walking. Each bar is showing the amount of time spent on your right and left legs. Or you can think of it as the amount of time spent with your right and left foot on the ground.

The dark blue bar on the left represents the amount of time spent on your left leg (or foot) while walking, and the light blue bar on the right side represents the amount of time spent on your right leg (or foot) while walking. If the bar on the left is taller than the bar on the right, then this means that you are spending more time on your left leg while you were walking. If the right bar is much taller than the left bar, then you are spending a lot more time on your right leg (or foot). The same is true if the right bar is taller.

Your goal is to make the right and left bars equal height, by evening out the amount of time spent on each leg while walking. Would you mind explaining it to me in your own words to make sure that we both understand?