Gait Asymmetry Post-Stroke

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy, Graduate Department of Rehabilitation Science, University of Toronto

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Abstract

This thesis examined post-stroke gait asymmetry: a prevalent issue and one that has a number of associated negative consequences (e.g. challenged balance control, gait inefficiencies, increased risk of musculoskeletal injury to the non-paretic limb and decreased overall activity levels). This thesis is comprised of three studies that focused on 1) how gait symmetry should be measured, 2) how gait asymmetry may change in the long term post-stroke and 3) whether gait asymmetry is responsive to a rehabilitation intervention. A comparison of the most common expressions of spatiotemporal gait symmetry revealed that the simple symmetry ratio calculation was most appropriate on the basis of ease of interpretation and clinical usefulness. Swing time, stance time and step length were found to be the most useful gait parameters to assess for symmetry. Although related, swing time, stance time and step length ratios exhibit variation in the discrimination of post-stroke individuals, in their inter-relationships and in their relationship velocity. When used together, swing time, stance time and step length asymmetry ratios may provide a complementary picture of the gait pattern and the quality of gait control. It was also demonstrated that swing time and stance time asymmetry were worse in later stages post-stroke when assessed cross-sectionally. In contrast, gait velocity did not exhibit this pattern. These results indicate that the control of gait
(symmetry) may decline over time post-stroke, independent from the capacity for gait which remains constant (velocity). This dissociation in characteristics supports the concept that these two variables (symmetry and velocity) may represent separate features of post-stroke gait. Finally, individuals with sub-acute stroke are capable of altering the temporal symmetry of their gait in response to visual biofeedback. Individuals with sub-acute stroke differ in terms of the strategy they employ in response to biofeedback and the observed improvements in gait symmetry were not always achieved in the desired manner: increased use of the paretic lower extremity. This thesis presents new information regarding the asymmetrical nature of post-stroke gait. Future work may extend these findings to develop a comprehensive approach to gait measurement as well as gait interventions that encourage increased paretic limb use instead of compensatory behaviour.
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**List of Abbreviations**

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<th>Description</th>
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<tr>
<td>6MWT</td>
<td>Six Minute Walk Test</td>
</tr>
<tr>
<td>ADL</td>
<td>Activities of Daily Living</td>
</tr>
<tr>
<td>BBS</td>
<td>Berg Balance Scale</td>
</tr>
<tr>
<td>BI</td>
<td>Barthel Index</td>
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<tr>
<td>BWS</td>
<td>Body Weight Support</td>
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<tr>
<td>CMSA</td>
<td>Chedoke-McMaster Stroke Assessment</td>
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<tr>
<td>CNS</td>
<td>Central Nervous System</td>
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<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>FAC</td>
<td>Functional Ambulation Category</td>
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<tr>
<td>FB</td>
<td>Feedback</td>
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<tr>
<td>FIM</td>
<td>Functional Independence Measure</td>
</tr>
<tr>
<td>FM</td>
<td>Fugl-Meyer Assessment</td>
</tr>
<tr>
<td>fMRI</td>
<td>Functional Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>GRF</td>
<td>Ground Reaction Force</td>
</tr>
<tr>
<td>ICF</td>
<td>International Classification of Function, Disability and Health</td>
</tr>
<tr>
<td>LE</td>
<td>Lower Extremity</td>
</tr>
<tr>
<td>MAS</td>
<td>Motor Assessment Scale</td>
</tr>
<tr>
<td>RAC</td>
<td>Rhythmic Auditory Cueing</td>
</tr>
<tr>
<td>RMI</td>
<td>Rivermead Mobility Index</td>
</tr>
<tr>
<td>SIS</td>
<td>Stroke Impact Scale</td>
</tr>
<tr>
<td>SW/ST</td>
<td>Swing time/stance time ratio (within one lower extremity)</td>
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<tr>
<td>TM</td>
<td>Treadmill</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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</tr>
<tr>
<td>TMT</td>
<td>Treadmill Training</td>
</tr>
<tr>
<td>TUG</td>
<td>Timed Up and Go Test</td>
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<tr>
<td>UST</td>
<td>Unilateral Step Training</td>
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1.0 Overview

Stroke is a very prevalent health issue in Canada with approximately 50,000 new cases reported in Canada each year\(^1\). The neurological disabilities associated with stroke affect all aspects of life including mobility, activities of daily living (ADLs), communication and cognition. Of these, walking function is the most commonly reported limitation\(^2\) and the one that receives the most attention in therapy\(^3\).

Post-stroke gait is characterized by a number of differences compared to the gait of healthy adults. These include altered spatiotemporal parameters, altered kinematic and kinetic profiles and increased energy costs. Spatiotemporal deviations of post-stroke gait receive the most attention both clinically and in research, with decreased velocity being the most widely documented and investigated. Another common deviation, and the focus of this thesis, is gait asymmetry. While walking velocity is suggested to be important for overall function, persisting gait asymmetry has more potential negative consequences. It is proposed that the asymmetrical gait pattern is inefficient, poses increased challenges to balance control, is associated with loss of bone mass density of the paretic hip and may increase the risk of musculoskeletal pain and joint degeneration of the non-paretic lower extremity (LE)\(^4,5\).

Symmetry may provide important insight about the control of walking, unique from more conventional measures such as velocity, and may have a role in guiding the clinician’s treatment decisions\(^5\). Despite the potential significance, there is no commonly accepted standard for either the method used to calculate symmetry or the gait parameter to assess. A standardized measure of symmetry could potentially benefit gait researchers and
clinicians treating gait dysfunction. A standard symmetry measurement will help to unify this field of gait research and facilitate comparison between studies. Clinically, a standard measure will facilitate discussion between clinicians and will serve as another means of describing and monitoring patient gait.

Gait asymmetry is prevalent in chronic stroke survivors with 55.5% of a group of ambulatory individuals exhibiting temporal asymmetry and 33.3% exhibiting spatial asymmetry\(^5\). What is not known is how gait and specifically gait symmetry may change over the long-term post-stroke. While there is some evidence of a decline in mobility after rehabilitation is complete\(^6-8\), there is little specific information with regards to how gait may change over time as measured by gait-specific indices such as symmetry. Given the associated negative consequences described above, it is important to determine if gait asymmetry has the potential to worsen in the long-term.

In addition to the need to understand how gait asymmetry may change after stroke, it is also important to determine if this feature of post-stroke gait is responsive to intervention. It is well established that both gait velocity and endurance are responsive to training\(^9-13\). In contrast, gait asymmetry is often considered resistant to general gait rehabilitation interventions\(^12,14,15\). This resistance to change may be attributable to the lack of specificity of previously investigated gait interventions. While some intervention studies have reported gait asymmetry values\(^11,12\), no intervention has been designed to specifically improve the temporal symmetry of post-stroke gait.
In spite of its potential importance, there remains relatively little insight regarding gait symmetry compared to other measures (e.g. velocity). To address these gaps in knowledge, this thesis investigated gait asymmetry in individuals post-stroke. The specific objectives of this work are:

1. to compare the properties of commonly used expressions of gait symmetry with the goal of achieving a recommendation regarding the most suitable candidate for standardization,

2. to investigate the potential for deterioration in gait over the long term post stroke using gait-specific measures (i.e. asymmetry and velocity),

3. to determine if sub-acute stroke patients could significantly alter their gait symmetry in response to visual biofeedback.

The following section provides a background on post-stroke gait and more specifically on the measurement and treatment of post-stroke gait. This is followed by 3 separate studies which were designed to achieve the main objectives listed above.

2.0 Background

2.1 Disability associated with stroke

Stroke is a very prevalent health issue in Canada. One Canadian will have a stroke every 10 minutes and there are approximately 260,000 Canadians currently living with the effects of stroke. Neurological disabilities resulting from stroke can affect all aspects of life including mobility, activities of daily living (ADLs), communication and cognition.
A study of community-dwelling seniors (aged 65 years and above) revealed that of those who had experienced a stroke, 87% were restricted in their ADLs and 42% could not walk or required mechanical assistance to do so, compared to only 37% and 10% respectively of people who had not experienced a stroke. Stroke costs the Canadian economy $2.7 billion a year in medical care, lost wages and decreased productivity. Acute care of stroke costs about $27,500 per person and inpatient and outpatient rehabilitation costs approximately $1060 per person and $740 per person, respectively.

In light of the significant number of stroke survivors, the cost of their care and the anticipated increasing prevalence of stroke as the baby boomer generation reaches 65, understanding and treating stroke-related disability is arguably a major priority.

### 2.2 Post-stroke gait

Stroke is associated with many impairments, of which, walking dysfunction is the most commonly reported limitation. Initially after stroke, half of individuals will have no walking function. After recovery and rehabilitation 64% of stroke individuals achieve independent walking function while 14% require some form of assistance and 22% remain unable to walk. In order to characterize the nature and degree of walking dysfunction among individuals with stroke, the profile of post-stroke gait has been studied using a number of different techniques including spatiotemporal gait parameters, oxygen consumption measures, electromyography (EMG), kinematics and kinetics. The profile of post-stroke gait is compared both within an individual using the gait profile of the non-paretic side as well as between individuals using the gait profiles of healthy adults.
Common spatiotemporal deviations of post-stroke gait include decreased gait speed\textsuperscript{20-22}, decreased cadence\textsuperscript{21,23}, decreased stride length\textsuperscript{23}, increased step width\textsuperscript{24}, and finally increased time spent in double limb support\textsuperscript{25} compared to healthy adults. A number of inter-limb deviations exist including prolonged swing phase on the affected side and prolonged stance phase on the unaffected side\textsuperscript{26}. These inter-limb deviations form the basis for a significant feature of post-stroke gait: asymmetry, which will be discussed in detail below.

In addition to being asymmetric and slow, post-stroke gait is also inefficient. Individuals with stroke walk shorter distances with higher oxygen consumption, indicating they walk with a higher oxygen cost (i.e. greater amount of oxygen consumed per unit distance travelled)\textsuperscript{27}. In other words, walking is an extremely demanding activity for individuals with stroke\textsuperscript{28}.

Post-stroke gait has also been studied extensively using EMG, kinematics and kinetics\textsuperscript{24,29-37}. In general, abnormal EMG findings associated with post-stroke gait can be grouped into two categories 1) alterations in amplitude of activity\textsuperscript{29,30} and 2) alterations in timing of activity with respect to the gait cycle\textsuperscript{29,30,32,33}. Similarly, Kim and Eng\textsuperscript{38} note that deviations in the kinematic and kinetic profiles of post-stroke gait feature alterations in 1) magnitude (e.g. angle ranges, peak powers and peak moments) and 2) pattern (i.e. shape and direction of curves). A large amount of inter-individual variation in EMG, kinematic and kinetic profiles exists\textsuperscript{38,39}. As a result, a large number of specific deviations have been described for each LE joint and each phase of the gait cycle,
however, no one individual will exhibit all of these deviations. Each individual exhibits a unique combination of these deviations that contribute to their gait dysfunction. These types of measurements are typically laboratory-based and are very rarely used in clinical practice due to lack of resources as well as a lack of clinical meaningfulness (either real or perceived.) Therefore these post-stroke gait features are outside the focus of this thesis and thus will not be discussed further. As mentioned above, slow velocity and asymmetry are two predominant features of post-stroke gait and will now be discussed in greater detail.

2.2.1 Gait velocity post-stroke

Reported values for preferred paced walking in chronic stroke patients range from 10cm/s\textsuperscript{40} to 76cm/s\textsuperscript{41} and in subacute patients from 13 cm/s\textsuperscript{42} to 65 cm/s\textsuperscript{21}. Less frequently measured is the maximum walking speed of stroke patients. Reported values for chronic patients range from 76cm/s\textsuperscript{43} to 109cm/s\textsuperscript{41} and for subacute patients from 22cm/s to 51cm/s\textsuperscript{42}. The wide variation observed in reported values is likely due to multiple factors including differences in measurement technique and equipment (e.g. 5m vs. 10m walkways, stop watch vs. motion capture systems), the amount of assistance allowed during measurement (e.g. walking aids, orthoses, external support) and the range in stroke severity and chronicity in study participants.

Post-stroke gait velocity has been studied extensively and is significantly associated with numerous variables. Gait velocity is related to general measures of gait and mobility including ordinal measures of gait independence and appearance\textsuperscript{21} as well as quantitative measures such as the number of steps taken in a day\textsuperscript{44}. Velocity is also associated with
various clinical scales including measures of motor\textsuperscript{22,41,45} and sensory\textsuperscript{45} recovery (such as the Functional Independence Measure (FIM) and the Fugl-Meyer Assessment (FM)), and measures of balance including subscales of the FM\textsuperscript{41} and the Motor Assessment Scale (MAS)\textsuperscript{46} as well as the Berg Balance Scale (BBS) \textsuperscript{46,47}. Taken together, this indicates that poor motor recovery and poor balance control may limit gait velocity in individuals with stroke. It also indicates that gait velocity is an important factor influencing an individual’s level of independence and function or ADLs.

Numerous studies have demonstrated that velocity is also related to strength of the paretic\textsuperscript{21,41,45,47-49} and non-paretic LE\textsuperscript{47,48}. However, the interpretation of this relationship is complicated by different methods of strength measurement (e.g. manual muscle testing, dynamometry, isokinetic machines), muscles measured and testing positions used across various studies. In addition, the relationship of velocity to LE strength in individuals with stroke is further complicated by the influence of age. There is evidence for a non-linear relationship between strength and gait velocity in older adults\textsuperscript{50}. Also, LE strength and velocity decline with age in a non-linear fashion\textsuperscript{51}. Therefore, strength becomes a more important determinant of gait velocity as a person ages and the impact of changes in strength on gait velocity is greater for those with strength below a particular threshold. This threshold is difficult to estimate but one attempt by Buchner and coauthors has identified 275 Nm as a possibility based on a composite LE strength score\textsuperscript{50}. The authors note that this threshold may be different for each individual depending on their physiological capacity in other determinants of gait velocity\textsuperscript{50}. This last point illustrates one more issue complicating the relationship between gait velocity and strength in
individuals with stroke. The impact of strength (or other determinants) on gait performance can be influenced by the individual’s position on the spectrum of gait dysfunction (i.e. from mild to severe.) For example, Patterson and colleagues\textsuperscript{47} found that determinants of long-distance walking were different for those individuals with a preferred velocity of $<$0.48m/s compared to those with a velocity of $>$0.48m/s.

Not surprisingly, gait velocity has been found to correlate with many other spatiotemporal gait parameters including cadence\textsuperscript{21,22,52}, stride length\textsuperscript{22}, double support duration\textsuperscript{22,52}, paretic and non-paretic stance duration\textsuperscript{22,36,52} and stride period\textsuperscript{22}. Interestingly, Roth and coauthors found that velocity had a greater number and stronger correlations with parameters of the non-paretic limb compared to paretic limb parameters\textsuperscript{52}. They suggest that this reflects non-paretic limb adaptations in response to changes in motor control of the paretic limb rather than some intrinsic characteristic of the non-paretic limb itself\textsuperscript{52}. This seems highly possible given that a significant proportion of the gait cycle is spent with the non-paretic limb in weight bearing\textsuperscript{52}.

To summarize, gait velocity is reduced in individuals with stroke although there is wide variation in the preferred velocity adopted by individuals. Decreased velocity is likely due to multiple factors including poor motor recovery, impaired balance and decreased strength and has a significant impact on an individual’s level of independence and ability to carry out ADLs post-stroke.
2.2.2 Gait asymmetry post-stroke

In contrast to velocity, gait symmetry receives relatively less attention, although interest in this characteristic of post-stroke gait is increasing. Spatiotemporal parameters are the gait variables most commonly analyzed for symmetry. Occasionally kinetic and kinematic parameters are used as well. Temporal symmetry calculations typically use swing time, stance time or an intra-limb ratio of swing to stance time (SW/ST), while spatial symmetry calculations use step length.

Normal gait is symmetrical in spatiotemporal parameters as well as kinetic and kinematic variables. The inter-limb difference of symmetry indices for both temporal parameters and ground reaction forces (GRF) is less than 6%\textsuperscript{37}. Temporal asymmetry of post-stroke gait is commonly described qualitatively as a prolonged paretic swing time and/or a prolonged non-paretic stance time compared to the contralateral limb\textsuperscript{22,26,37,49,53-55}. In contrast, the pattern of spatial or step length asymmetry is less consistent. Some individuals with stroke may exhibit longer paretic step lengths while others exhibit longer non-paretic step lengths\textsuperscript{37,45,55,56}.

Temporal gait asymmetry has been found in 55.5% of a group of individuals with chronic stroke and spatial asymmetry was less prevalent, affecting 33.3% of the same group\textsuperscript{5}. The values of symmetry are difficult to compare across studies due to the different equations used to calculate symmetry and the different gait parameters analyzed. However, of the studies that use a simple ratio: reported values for swing time asymmetry range from
1.23\textsuperscript{55} to 1.61\textsuperscript{22} (expressed as paretic/non-paretic) and one study reported a mean step length symmetry ratio value of 1.08\textsuperscript{5} (expressed as non-paretic/paretic).

Given the prevalence, reduction of asymmetry in post-stroke gait is commonly addressed by rehabilitation therapists\textsuperscript{53}. However, there exists an opposing view which suggests that gait asymmetry should not be changed, particularly in the chronic stage. According to this point of view, gait asymmetry is a positive adaptation to the neurologic deficits associated with stroke that affords individuals a certain level of gait function. For example, Griffin and coauthors\textsuperscript{57} examined the relationship of various kinematic and kinetic variables to gait velocity and concluded that the promotion of gait symmetry post-stroke would not result in an increase in gait velocity. These investigators argue that aiming for biomechanical symmetry in a body system that is in a stable state (i.e. chronic stroke) is less justifiable since it is unlikely to achieve optimal performance\textsuperscript{57}.

In contrast, this thesis views gait asymmetry post-stroke as a change in the gait pattern to accommodate stroke related impairments that influence and/or interfere with the control of gait. It is the position of this thesis that the reduction of temporal gait asymmetry is an important clinical goal since it may be associated with a number of negative consequences. The proposed negative consequences are: 1) challenges to dynamic balance control, 2) gait inefficiencies, 3) cumulative musculoskeletal injury to the non-paretic LE, 4) loss of bone mass density in the femoral neck of the paretic LE, and 5) reduced activity levels which may occur in response to any one or combination of the preceding consequences.
There is limited evidence linking gait asymmetry directly to these negative outcomes in the stroke patient population. However, several lines of indirect evidence support these arguments and they will be outlined in the following paragraphs.

The incidence of falls is higher in community-dwelling stroke individuals than in the general healthy elderly population\(^5\). The majority of falls occur during walking\(^6\) which suggests that dynamic balance control during gait is an issue. It is possible that the asymmetrical loading of the non-paretic limb associated with temporal gait asymmetry contributes to this difficulty in dynamic balance control by impeding compensatory stepping behaviour. Correlations between temporal gait symmetry ratios and balance measures\(^5\,^4\,^5\) suggest that there is a link between asymmetrical gait and challenges to balance control.

As mentioned previously, post-stroke gait has a higher metabolic cost, even for younger stroke patients, compared to healthy gait\(^6\,^0\,^6\,^2\). Gait symmetry and energy expenditure are believed to be related and symmetric gait is considered to be the most efficient pattern\(^6\,^3\,^6\,^4\). Therefore, it is possible that the asymmetric pattern contributes to the observed increased metabolic cost of post-stroke gait.

Gait asymmetry may also be associated with cumulative musculoskeletal injury, joint degeneration and joint pain in the non-paretic limb. Although there are no studies that have examined this relationship in the stroke population: studies of the amputee population have demonstrated this link. The amputee gait pattern is also asymmetric with
individuals spending more time in stance on their intact limb. This gait pattern is associated with increased, loading through the intact limb in both amputee\textsuperscript{65} and stroke\textsuperscript{37} individuals. High forces repetitively applied to a limb can lead to joint pain and degeneration. Therefore, the increased, cumulative loads applied to the intact limb as a result of walking asymmetrically, may lead to increased prevalence of musculoskeletal complaints in a patient compared to the healthy population. Indeed, the prevalence of knee pain in the intact limb of a group of amputee patients was found to be 40.3\% compared to only 20.2\% in a group of healthy adults\textsuperscript{66}. It seems reasonable to assume that the incidence of musculoskeletal injury and pain would be increased in stroke patients who exhibit a similar gait pattern, however this remains to be investigated.

Musculoskeletal complications may also arise in the paretic limb as a result of persisting gait asymmetry. Jorgensen and coauthors\textsuperscript{4} found a significant association between asymmetry in weight-bearing during standing and loss of bone mineral density in the paretic lower limb. The authors also note that their findings may underestimate the relationship between gait asymmetry and bone mineral density loss since bone adaptation is driven by dynamic rather than static loading\textsuperscript{4}.

Finally, the ambulatory profiles of individuals with stroke are extremely low (2837 steps/day) even when compared to sedentary healthy older adults (5000-6000 steps/day)\textsuperscript{62}. Although multiple factors play a role in determining how much an individual walks in a day, it is possible that the proposed consequences of persisting gait asymmetry contribute, in part, to the restriction of overall activity levels in individuals with stroke.
To summarize, although direct evidence of the consequences of persisting post-stroke gait asymmetry is limited, several lines of indirect evidence suggest that the asymmetrical gait pattern may pose several complications for the individual with stroke. Furthermore, the cumulative effects of asymmetrical gait may lead to the restriction of walking activity and the limitation of function and participation in individuals with stroke in the long term.

There are differing reports on the relationship of temporal and spatial symmetry to velocity. A number of studies have found a weak to moderate relationship between the various temporal symmetry measures and velocity with correlation coefficients ranging from 0.41 to 0.58\(^5,22,37,52\). One study found no significant relationship between velocity and stance symmetry or SW/ST symmetry\(^52\). The variation in study results can be attributed to numerous factors. First, as mentioned above, different studies employ different equations to calculate symmetry (i.e. ratio or index). Second, each study had subjects with different levels of walking ability. For example, reported values for group mean walking velocity range from 0.31m/s\(^22\) to 0.82m/s\(^37\). Third, studies vary in the level of assistance allowed during the walking task used to measure symmetry (e.g. use of gait aids and orthoses) which may affect asymmetry\(^67\). Finally, the disease chronicity varied between studies with reported mean time post-stroke values ranging from months to years. Overall, however, there appears to be a negative relationship such that those with greater temporal asymmetry walk at slower speeds. One study, with a larger sample size representing a larger range of walking ability, characterized the negative relationship between SW/ST symmetry and velocity as non-linear, noting that the relationship was more strongly distinguished in individuals who walked very slowly (approximately
<60cm/s). In contrast individuals with a walking velocity >60cm/s may or may not exhibit temporally asymmetric gait\textsuperscript{5}.

The relationship between spatial (step length) symmetry and velocity is less clear with one study by Balasubramanian and coauthors finding a significant weak correlation\textsuperscript{56} and two studies finding no significant relationship\textsuperscript{5,37}. These differences might be explained by the fact that the gait measurement protocol employed by Balasubramanian and coauthors permitted participants to use gait aids while the protocol used in the remaining two studies did not. The use of aids may alter the degree of asymmetry thereby affecting the relationship with velocity. However, taken all together, these results suggest that spatial asymmetry does not necessarily limit the walking velocity an individual may attain\textsuperscript{56}. Alternatively, the inability to detect a relationship may be due to the higher variability in the direction of step length asymmetry (i.e. longer paretic or longer non paretic step length) compared to temporal asymmetry\textsuperscript{37}.

Another important feature of the relationship between both temporal and spatial asymmetry and velocity is revealed by examining the respective direct impairments with which they are associated. A study by Hsu and colleagues\textsuperscript{45} revealed different primary determinants for velocity and gait symmetry. This suggests gait velocity and gait asymmetry are independent features of post-stroke gait that need to be addressed with separate rehabilitation interventions.
Like the relationship to velocity, the relationship between gait symmetry and motor impairment is complex. Multiple studies have reported moderate correlations with various measures of motor impairment (e.g. Brunnstrom staging, the FM and the Chedoke-McMaster Stroke Assessment (CMSA)). Reported correlation coefficients range from 0.63 to 0.72 for temporal symmetry and 0.44 to 0.53 for spatial symmetry\textsuperscript{5,22,45,45,56}. While this indicates that motor impairment has some association with the temporal and spatial symmetry of gait, it seems that it does not explain all of the variance observed in the stroke population. Furthermore, it has been demonstrated that individuals with the same level of motor impairment, as measured by Brunnstrom stages and CMSA scores, can exhibit different degrees of asymmetry\textsuperscript{5,22}. These discrepancies demonstrate two important points: 1) clinical measures of motor impairment may not be sensitive enough to discriminate individuals differing in performance of complex motor tasks such as gait and 2) factors in addition to motor impairment must influence gait asymmetry.

A few studies have attempted to relate more specific or direct measures of body impairment to gait asymmetry in an effort to reveal its underlying causes. Like clinical measures of motor impairment, these more specific measures are unable to explain all the variance in gait asymmetry. However, they do reveal important differences between temporal and spatial asymmetry. Two major groups of impairment measurements have been used to investigate gait symmetry: 1) paretic ankle impairments and 2) postural instability. The first category, ankle impairments, appears to be an important determinant of gait asymmetry\textsuperscript{45,49}. Impaired joint position sense, decreased dorsiflexor strength and
plantarflexor spasticity are related to greater temporal asymmetry\textsuperscript{45,49}. In contrast, plantarflexor spasticity and impaired propulsive force generation are associated with greater spatial asymmetry\textsuperscript{45,49,56}. However, spasticity and propulsive force generation may not represent separate factors determining step length asymmetry. Lamontagne and coauthors note that spasticity is negatively correlated with gait velocity and is believed to compromise the efficiency of ankle push-off\textsuperscript{68}. Therefore, spasticity might be a determinant of step length asymmetry because it limits the propulsive force generation of the paretic leg.

The second category of body impairment, postural instability, indicated by increased posterior postural sway, is also related to increased temporal gait asymmetry\textsuperscript{54}. Increased backwards sway exhibited by an individual with stroke is associated with increased temporal gait asymmetry\textsuperscript{54}. The link between postural control and gait symmetry was also demonstrated in a study by Kim and coauthors\textsuperscript{37}. The investigators found that symmetry of GRF measured during the stance phase of gait is significantly correlated with temporal but not spatial gait symmetry\textsuperscript{37}. Symmetrical weight bearing between the two lower limbs is related to more temporally symmetrical gait suggesting that they both may be influenced by similar factors such as postural control\textsuperscript{37}.

In summary, motor impairment, specific ankle impairments and postural control are related to temporal and/or spatial gait symmetry. In general, the difference in these associations taken together with the difference in the relationship to velocity, suggests
that while there is likely some degree of relation, temporal symmetry and spatial
symmetry may reveal separate features of gait.

2.3 Measurement of post-stroke gait

The measurement of post-stroke gait is essential for investigations into both the features
of post-stroke gait and the effectiveness of gait interventions. There are several methods
to measure post-stroke gait. These methods can be grouped into three major categories: 1) clinical scales, 2) clinical performance-based measures and 3) laboratory measures.

Walking is a complex motor task that can be measured from many different perspectives. To simplify this discussion, this section will use the World Health Organization’s (WHO) model of disability called the International Classification of Function, Disability and Health (ICF) which “provides a standard language and framework for the description of health and health-related states”\textsuperscript{69}. Using this model, the term ‘impairment’ refers to problems in body function (physiological functions) or structure (anatomical parts) such as a significant deviation or loss. The ICF defines the term ‘activity’ as “the execution of a task or action by an individual”\textsuperscript{69}. This thesis will use the terms activity and function interchangeably.

A systematic review, by Mudge and Stott, of 357 studies of post-stroke gait found that some of the most common clinical scales used to assess walking ability are: the Barthel Index (BI) (20% of studies), Functional Ambulation Categories (FAC)(10% of studies), the Motor Assessment Scale (MAS) (6% of studies) and the Rivermead Mobility Index (RMI) (5% of studies)\textsuperscript{70}. All of these scales have established reliability\textsuperscript{71-74} and validity\textsuperscript{75-78}. However, none of these scales, with the exception of FAC are specific to walking.
Instead, these scales contain test items that measure various aspects of mobility (e.g. transfers from supine to sitting, rising from a chair) with a few test items (1 to 5) that directly address the ability to walk.

All of these clinical scales measure mobility and specifically walking at the level of activity or function. They do not provide insight to the underlying impairments contributing to a patient’s gait dysfunction. Although some measures (e.g. RMI) have demonstrated sensitivity to change over the rehabilitation period\textsuperscript{78}, it is unlikely that they are sensitive enough to detect subtle changes in the gait pattern due to either intervention or decline. This limitation stems from an inherent weakness of clinical scales: ambiguity in the resultant scores\textsuperscript{55}. In other words, individuals may attain the same score but functionally are very different\textsuperscript{55}. For example, Cunha and coauthors conducted a study of gait measures in acute stroke patients and found 8 subjects with an FAC score of 2 that exhibited pronounced variability in velocity (0.13 to 0.91m/s) and walking distance over 5 minutes (10.6 to 162m)\textsuperscript{28}. Furthermore, some of these scales have reported floor and/or ceiling effects\textsuperscript{79-81}. These clinical scales measure at the level of activity or an individual’s overall gait function.

The second category of gait measures are clinical, performance-based measures such as the 6 Minute Walk Test (6MWT) and the Timed Up and Go Test (TUG). Mudge and Stott reported their frequency of use in the post-stroke gait literature as about 8% each. The 6MWT is a submaximal measure often used to assess functional capacity: the extent to which an individual can increase exercise intensity and maintain that increased level\textsuperscript{82}. 
It has established reliability and validity for use in the stroke population\textsuperscript{79,83}. Although, highly correlated with gait speed, the 6MWT measures a distinct aspect of walking ability that may be reflective of an individual’s functional capacity for ADLs\textsuperscript{79,82}. The TUG, by comparison is a basic test of functional mobility\textsuperscript{84}. It also has established reliability and validity for individuals with stroke and can discriminate stroke patients from healthy elderly individuals\textsuperscript{83,85}. These performance-based measures have several advantages over clinical scales: they are quantitative and are more objective, they have better discriminative ability and they are sensitive enough to detect change in a patient’s status. However, like the clinical scales, these performance-based measures provide an index of a patient’s overall walking function, not the underlying impairments.

Clearly, the psychometric properties of commonly used clinical scales and performance-based measures are well documented. While validity, reliability and responsiveness are undeniably important attributes, it is also important to consider the information required of a measurement\textsuperscript{70}. Information derived from these two types of clinical measures can be described as functional or activity-related. That is, they give an evaluation of the general walking ability of an individual: Can they walk a certain distance?, Do they require assistance of another individual?, Do they use a walking aid or orthosis? While valuable, this information does not provide insight to the impairments contributing to the observed walking dysfunction.

While an index of a patient’s mobility status can be used for the purposes of measuring outcomes, summarizing a case and inter-professional communication: it will not assist in
directing therapeutic intervention. Measurements of impairments contributing to an individual's gait dysfunction can help guide clinical decisions about appropriate interventions to improve gait function. It has been noted that even among stroke patients with significantly decreased gait function, the combination of gait deviations can differ markedly\textsuperscript{34}. Gait measurement must therefore, be able to detect and measure these deviations or impairments that contribute to the overall walking dysfunction of a patient.

The third category of gait measures, laboratory measures, addresses this issue more effectively than clinical performance based measures. Included in this category are EMG, joint kinematics, kinetic measures and spatiotemporal gait parameters. A few attempts have been made to create classification systems for stroke patients based on either EMG\textsuperscript{30} or kinematic\textsuperscript{34} profiles. While these systems provide insight to the contributing deviations/impairments of post-stroke gait and could be used to guide treatment, they are unlikely to be adopted clinically, as mentioned earlier, due to the lack of sufficient resources (including equipment, space and personnel) to carry out these types of data collection and analyses.

Spatiotemporal parameters are the most common objective laboratory measurement method employed in post-stroke gait studies. Commonly reported parameters include step length, stride length, cadence, step time, stride time and velocity. Of all the spatiotemporal parameters, and even more generally, of all gait measures, velocity is the mostly widely reported\textsuperscript{70,86} and is believed to be a good indicator of overall gait performance or walking ability\textsuperscript{22,43,44,52,87-89}. Furthermore, the remaining temporal gait
parameters (e.g. swing time, stance time, cadence) are highly correlated to velocity and therefore, according to Brandstater and colleagues, their inclusion in gait measurement does not “further characterize the pathologic nature” (p.586) of post-stroke gait\textsuperscript{22}. Most of the relevant temporal information about post-stroke gait is included in velocity\textsuperscript{22}.

Velocity exhibits good test-retest and inter-rater reliability\textsuperscript{72,76,83,90} and is sensitive for detecting clinically important changes\textsuperscript{90}. The reported predictive value of gait velocity varies. A study by van de Port and colleagues found that gait velocity measured in the clinic can predict walking velocity in the community in higher functioning individuals (i.e. velocity >0.8m/s)\textsuperscript{91}. However, Goldie and colleagues found that gait velocity measured at admission to inpatient rehabilitation poorly predicted velocity at discharge\textsuperscript{92}. Perhaps more important clinically than predictive value, is the discriminative ability of velocity. Compared to the FIM and MAS, gait velocity has stronger discriminative ability among higher functioning individuals with stroke\textsuperscript{93}. In addition, a speed-based classification system, initially proposed by Perry et al\textsuperscript{40}, has proven useful. This system divides individuals, based on their preferred velocity, into clinically meaningful, functional ambulation classes as follows: household ambulation (<0.4m/s), limited community ambulation (0.4-0.8m/s) and full community ambulation (>0.8m/s)\textsuperscript{88}.

Individuals who transition to a higher speed-based category by increasing their preferred velocity, demonstrate improved function and quality of life as measured by the Stroke Impact Scale (SIS)\textsuperscript{88}. In addition, these speed-based categories have been validated by two objective, quantitative measures: 1) steps taken per day as a measure of home and community walking behavior and 2) the percentage of total propulsion generated by the
paretic leg during gait (an impairment-level measure)\textsuperscript{44}. Both of these objective measures were able to differentiate the speed-based groups\textsuperscript{44}.

Clearly velocity is a useful measure of post-stroke gait function but it exhibits some of the same limitations as clinical scales and performance-based measures. Wade and coauthors\textsuperscript{87} have noted that “measuring speed does not help diagnose the underlying physiological disturbance needing treatment” (p.29). In other words, when used as a solitary measure, velocity neither assists in understanding the nature of gait deficiencies nor is it helpful in directing rehabilitation interventions. Olney and coauthors note that, velocity lacks, what Cappozzo terms “explicative capacity”(p.302)\textsuperscript{36,94}. For example, individuals with similar velocities can exhibit vastly different kinematic and EMG patterns\textsuperscript{34}. Presumably, each of these patterns would indicate different therapeutic approaches which the clinician would not be able to elucidate if velocity alone was measured. Furthermore, intervention based on the measurement of velocity and the goal of improving it may be successful. However, it is possible that “compensatory action by the non-paretic leg can result in a relatively functional walking speed despite poor coordination of the paretic leg”(p.872)\textsuperscript{86}. That is, increased velocity can be achieved without addressing underlying impairments contributing to gait dysfunction.

Various impairment-level laboratory gait measures have been proposed including the propulsive force of the paretic leg (using GRF)\textsuperscript{86} and a dynamic measure of plantarflexor spasticity (using EMG)\textsuperscript{68}. While these measures are reliable and capable of discriminating various levels of impairment within a stroke group, they are also labour
and resource intensive for the current clinical environment. Given this, it is unlikely these measures will be adopted for clinical use in the near future despite their potential for explicative capacity.

One practical alternative gait-impairment measure is symmetry. Gait symmetry may come closer to measuring gait-related impairments than velocity. For example, Kim and colleagues note that swing symmetry better represents impairment as it is directly related to the ability to stand on one leg. Numerous investigators have highlighted the value of gait symmetry measures and suggest that such a measure provides additional, non-redundant information that cannot be gained by measurement of walking speed alone. Symmetry measures are considered to be indicators of the quality of gait or alternatively the control of gait. These measures have demonstrated concurrent validity and are reliable in as much they are derived from spatiotemporal measures that have good reliability. Others have suggested that measures of gait symmetry can guide the design of gait rehabilitation programs that address the unique deficiencies, or underlying impairments, of each patient. Compared to gait velocity, the measurement properties and discriminative abilities of gait symmetry are less frequently studied. Previous studies have demonstrated that gait symmetry may further discriminate a group of individuals with stroke than either motor impairment measures or velocity could alone.

2.4 Treatment and recovery of post-stroke gait

As mentioned previously, improvement in walking function is the goal most often stated by stroke patients. Furthermore, limitations in walking can profoundly impact
independence, quality of life and participation. Therefore, a significant portion (25-45%) of physiotherapy time is spent addressing gait dysfunction. Many rehabilitation approaches to improving post-stroke gait exist and the following discussion will focus on the ones used most commonly in clinical practice: Bobath (or Neurodevelopmental Theory in America) intensive exercise and/or mobility training and treadmill training.

2.4.1 Treatment Approaches to Rehabilitation of Post-stroke Gait

Surveys of physiotherapists in the United Kingdom, Australia, Sweden and the US have all demonstrated that Bobath/NDT is the preferred approach to rehabilitation of stroke patients. This approach has evolved since it was initially developed in the 1950s, but the original guiding concept of promoting recovery of the affected limbs rather than teaching compensations with the unaffected limbs remains. In its current form, the Bobath approach is aligned with the ICF, acknowledging the continuum of human function as well as the unique nature of an individual’s limitations. The main foci of Bobath-based interventions are a) the integration of postural control and task performance, b) control of selective movement for the production of coordinated motor patterns and c) the contribution of sensory inputs to motor control and motor learning.

Patient’s functional goals are primarily accomplished through the following process: analysis of movement and task performance, identification of activity limitations, hypothesis generation regarding the underlying impairments and intervention aimed at the impairment and/or activity level. One predominant Bobath intervention is facilitation. Facilitation is defined by the International Bobath Instructors Association as “part of an active learning process in which the individual is enabled to overcome inertia,
initiate, continue or complete a functional task". It is identified as “one way of using sensory and proprioceptive controls to make movement easier”. Bobath-based gait interventions have been associated with significantly improved spatiotemporal gait parameters (e.g. decreased duration of paretic weight acceptance and increased duration of paretic single limb support) and improved scores on clinical scales (e.g. MAS and BI). However, despite these reported improvements, there is conflicting evidence regarding the achievement of the main therapeutic goal of the Bobath approach: restoration of normal movement patterns. Two studies (n=9 and n=148) revealed that a Bobath-based gait intervention did not achieve this goal (as measured by kinematic and kinetic variables). In contrast, one study (n=2) by Lennon demonstrated improved kinematic profiles (e.g. increased knee extension and improved ankle dorsiflexion during paretic stance) after approximately 30 therapy sessions, indicating more normal movement patterns during gait. The discrepancy in results may be attributed to the fact that the study by Lennon utilized a pre-post test design within subjects, whereas the other two larger studies reported on group mean differences. It is possible that the latter studies were unable to detect significant within subject changes within their study group. Despite some positive pre-post results, the Bobath approach does not fare well when compared to other therapeutic approaches. Bobath-based physiotherapy has been compared to more recently developed interventions including motor relearning (task-oriented) interventions, strength training, treadmill training (TMT) with body-weight support (BWS), TMT with rhythmic auditory cueing (RAC), and EMG visual biofeedback. Two systematic reviews have both concluded that Bobath-based physiotherapy is no better or inferior to other approaches at improving gait as evaluated
by a variety of indices including velocity, symmetry and clinical scales (e.g. FAC)\textsuperscript{113,114}. It is interesting then, given the lack of evidence supporting the superiority of the Bobath approach, that it remains a common choice among physiotherapists treating stroke patients. Clearly, physiotherapists feel strongly about the effectiveness of the Bobath approach. The inability to find empirical evidence of its superiority may be due to the diverse opinions as to what constitutes Bobath-based therapy which makes it difficult to standardize and document interventions for studies\textsuperscript{113}. Wade\textsuperscript{115} suggests that “the greatest difficulty in rehabilitation research is to define accurately the intervention being studied”. Efforts have been made to clarify the definition of Bobath therapy\textsuperscript{103} and describe specifics of the clinical practice of Bobath\textsuperscript{104}. Further investigations into the efficacy of Bobath should be guided by these efforts so that more rigorous operational definitions can be employed and the exact content, schedule and intensity of therapy can be recorded in order to improve upon the methodological issues of efficacy studies\textsuperscript{113}.

The second approach to post-stroke gait rehabilitation is intensive exercise and/or mobility training. An alternative label for this approach is “task-oriented” gait training\textsuperscript{116}. These training programs generally approach gait within the broader context of mobility and incorporate repetitive practice of a variety of mobility tasks\textsuperscript{113}. This type of intervention is commonly administered as a circuit training class and includes at least two of the following three elements: 1) graded strengthening using functional tasks (e.g. repetitive rising from a chair), 2) aerobic training (e.g. cycle ergometry) and 3) a battery of walking tasks with challenging postural control demands (e.g. stepping over obstacles)\textsuperscript{113,116}. A review by Wevers and coauthors\textsuperscript{116} cite three advantages of a circuit
training class: 1) it allows patients to practice intensively in a meaningful and progressive way, 2) it uses resources and therapist time efficiently compared to individual therapy and 3) it creates a group dynamic that provides peer support and social interaction which may enhance compliance and impart psychosocial benefits. One disadvantage of this approach is the requirement of ambulation for 10m independently or with supervision for participation\textsuperscript{113}. This is due to the fact in the circuit class format the ratio of patients to therapist is approximately 4 or 5 to 1 which means that close guidance and supervision is not as readily available as it would be in the traditional one to one therapy setting. Therefore, task-oriented, circuit training is not suitable for more severely affected and/or non-ambulatory individuals. This approach has been implemented successfully in a subacute stroke group, with individuals exhibiting significant improvements in gait velocity\textsuperscript{117,118}, 6MWT distance\textsuperscript{117,118}, and TUG time\textsuperscript{117}. However, the effectiveness of task-oriented training is more commonly investigated in the community-dwelling, ambulatory chronic stroke population\textsuperscript{113}. Chronic stroke individuals participating in task-oriented training demonstrate improved walking ability as measured by 6MWT performance (i.e. distance and velocity)\textsuperscript{119-121} and gait velocity\textsuperscript{120}. They also derive a number of other benefits (some of which are related to gait function) including improved cardiorespiratory fitness (as measured by maximum oxygen consumption), improved paretic LE isometric strength and maintenance of hip bone mass density\textsuperscript{119}. Finally, these programs are associated with improvement in activity, health and quality of life when measured over the long term (i.e. 1 year)\textsuperscript{121}. 
Task-oriented training has also been shown to be superior to other rehabilitation approaches. Two systematic reviews of post-stroke gait interventions support the use of task-oriented circuit class training to improve gait over other forms of therapy. Significant effect sizes have been reported for 6MWT distance\textsuperscript{113,116}, gait speed\textsuperscript{113,116} and TUG\textsuperscript{116} in favour of task-oriented, circuit training compared to a control group (usually described as ‘traditional therapy’).

The results of task-oriented approaches also demonstrate one significant principle of successful gait rehabilitation: task specificity. Blennerhassett and Dite\textsuperscript{117} observed that functional gains made by stroke participants are specific to the type of task-oriented practice they receive. In their randomized controlled study, only the group receiving upper extremity task-oriented practice (e.g. reach to grasp and hand-eye coordination activities) improved in measures of hand and arm function (e.g. Jebsen Taylor Hand Function Test) whereas only the group receiving mobility training improved in 6MWT performance\textsuperscript{117}.

A third, common approach to post-stroke gait rehabilitation is treadmill training. Treadmill training is administered both in isolation and paired with other adjunct interventions including BWS, RAC and unilateral step training. The modern concept of motor learning and motor recovery is that repetitive practice of a task can facilitate the development of new motor programs or the refinement of existing programs in order to improve performance of the task\textsuperscript{31,113}. This repetitive practice can facilitate the integration of spared and altered sensory and motor systems following a stroke\textsuperscript{113}. TMT
is able to provide task-specific repetitive practice of walking as it provides continuous practice of complete complex gait cycles versus the isolated, gait preparatory tasks performed in traditionally-based programs (e.g. Bobath)\textsuperscript{31,122,123}. It is believed that task-repetitive training on the TM can induce adaptive neuroplastic changes in the injured brain leading to improved walking function\textsuperscript{13,124}. Preliminary evidence from a functional magnetic resonance imaging (fMRI) study suggests that TMT produces increased activation of cortico-subcortical networks which may be the mechanism (either through plasticity or compensatory activation) by which TMT induces improvements in gait post-stroke\textsuperscript{124,125}.

Basic TMT, at an individual’s preferred speed, has been associated with improved walking function. Individuals who underwent a TMT program have demonstrated improved FAC scores\textsuperscript{10}, increased gait velocity\textsuperscript{10,12}, increased cadence\textsuperscript{12}, increased stride length\textsuperscript{12} and 6MWT distance\textsuperscript{12}. When TMT is performed using a formula of progression for aerobic training, it also improves cardiovascular fitness as evidenced by reduced energy expenditure\textsuperscript{126} and increased VO\textsubscript{2} peak\textsuperscript{13}. Finally, it has been shown that rather than training at the preferred speed, TMT with the goal of increasing the belt speed at each session, is more effective at improving gait parameters including velocity, cadence, stride length and FAC scores\textsuperscript{9}.

BWS is often paired with TMT in order to provide compensation for impaired postural control, thereby allowing even severely affected individuals to walk on a TM\textsuperscript{11}. TMT with BWS is associated with improved kinematic gait profile (e.g. greater knee flexion in
the swing phase, greater knee extension in the stance phase)⁴¹, improved 6MWT performance⁴¹,⁴², increased velocity⁴²,⁴³ and improved scores on the FAC and BI⁴².

Despite many individual studies demonstrating improvement in gait with TMT and TMT with BWS, a recent Cochrane review by Moseley and coauthors⁴⁹ found no statistically significant effect of TMT with or without BWS and no evidence of its superiority to other interventions. At best, TMT is at least as effective as other interventions with little risk of harm⁴⁹. However, there is some evidence that TMT with BWS is superior to TMT alone for individuals with stroke who are unable to walk without physical assistance⁴⁹. In addition, TMT in combination with task-oriented exercise may be more effective than control interventions⁴⁹. It is also possible that factors such as differentiating between dependent and independent walkers, dosage and intensity of interventions and the chronicity of disease may affect TMT outcomes and therefore need to be accounted for in future studies⁴⁹. The authors of the Cochrane review conclude that there is a need for well-designed large-scale studies to further evaluate the effects of TMT and BWS on post-stroke gait⁴⁹.

There are a small subset of TMT studies that have modified TM walking or combined TM walking with an adjunct intervention. The aim of these novel interventions is usually to improve coordination of the gait pattern during TM walking. In a study by Roerdink and coauthors⁵⁰, 9 individuals with stroke ambulated on a TM while computer-generated rhythmic acoustic pacing stimuli were administered alternately to the left and right ears through earphones. Compared to TM walking alone, TM walking with acoustic pacing
was associated with significantly improved step length symmetry, step time symmetry and a measure of interlimb coordination/relative timing between limbs. Two other studies have used a modified TM paradigm to improve post-stroke gait. Kahn and Hornby designed a novel paradigm termed unilateral step training (UST) in which 18 individuals with stroke stood beside a TM with the unaffected LE on the TM belt and the affected LE off the belt at the same height. BWS and hand support were provided as necessary. For 20 minutes, individuals took steps with their unaffected LE on the moving TM belt. UST resulted in immediate improvements in step length asymmetry of OG walking and these changes were retained at follow up two weeks later. Finally, Reisman and coauthors were able to demonstrate improvements in the gait pattern of 13 individuals with stroke using a different TM modification: split-belt TM walking. This approach uses a specialized TM with two separate belts that can be controlled independently. The two belts operate at either the same speed or different speeds. The authors demonstrated that the immediate after-effects of split-belt TM walking produced greater symmetry in step length, double support time and improved inter-limb coordination during regular TM walking.

Although these novel TMT paradigms are unlikely to be adopted in the clinical setting any time soon, they are significant because they demonstrate two important points. First, these TMT programs demonstrate that the injured nervous system is capable of producing a more coordinated gait pattern. Second they demonstrate that individuals with stroke are capable of performing complex gait retraining tasks (likely with varying degrees of success) that require their attention on some external stimuli while walking on a TM.
Therefore, the focus or aim of post-stroke gait interventions does not need to be limited to increasing velocity and walking distance. It is also possible to design new gait interventions with the goal of improving the control of gait post-stroke.

2.4.2 Recovery of Gait Post-stroke

Approximately two thirds of acute patients exhibit impaired walking function initially after stroke. Various studies have examined recovery of walking function after stroke by following individuals soon after the onset of stroke, over a period of inpatient rehabilitation. The majority of these studies use the clinical scales (described in the previous section on gait measurement) and/or velocity, to describe the recovery of walking function. In general, these studies report an early rapid phase of recovery with most of recovery occurring within the first 3 months post stroke. Although it has been reported that the majority of stroke patients (50-64%) regain “independent” walking function, this may actually underestimate the extent of walking impairment after stroke due to the reliance on clinical scales to measure gait. For example, Wade and coauthors note that despite regaining independence, many patients remain disabled because they walk slower than age-matched healthy adults. As described in the previous section on treatment, there are many rehabilitation interventions that are effective at improving various features of post-stoke gait. However, it is important to note that although some recovery occurs with rehabilitation, the majority of individuals are still left with significant gait impairments and functional limitations. Therefore, there is a continuing need to improve gait rehabilitation of post-stroke gait. This can be done with a two-pronged approach: 1) improving the measurement of post-stroke gait to guide and
monitor treatment and 2) develop new gait retraining programs that address more than just the level of independence, velocity and distance walked.

2.5 Summary

In summary, walking is frequently affected after stroke and improvement of walking function is the goal most often stated by patients. Post-stroke gait features a number of deviations from healthy gait. One of these deviations is gait asymmetry which is prevalent in the post-stroke population. Asymmetry is an important issue to address in the rehabilitation of post-stroke gait for several possible reasons including efficiency, balance control, musculoskeletal health and overall activity level. In addition, gait symmetry may serve as a measure of gait control that can provide additional, non-redundant information that cannot be gained by measurement of walking speed alone. The following three chapters detail studies addressing important issues related to understanding post-stroke gait asymmetry: 1) how symmetry should be measured 2) how asymmetry may change in the long-term post-stroke and 3) whether gait asymmetry is responsive to a rehabilitation intervention.
3.0 Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization.

3.1 Abstract
Symmetry is a gait characteristic that is increasingly measured and reported, particularly in the stroke patient population. However, there is no generally accepted standard for assessing symmetry making it difficult to compare across studies and establish criteria to guide clinical decision making. This study compares the most common expressions of spatiotemporal gait symmetry to describe post-stroke gait and makes recommendations regarding the most suitable symmetry measure for standardization. We made comparisons between the following commonly used symmetry measures: symmetry ratio, symmetry index, gait asymmetry and symmetry angle using step length, swing time, stance time, double support time and an intra-limb ratio of swing:stance time.
Comparisons were made within a group of 161 community-dwelling, ambulatory individuals with stroke and 21 healthy adults as a reference group. Our analysis supports the recommendation of the symmetry ratio as the equation for standardization and step length, swing time and stance time as the gait parameters to be used in the equation. Future work should focus on establishing the reliability and validity of these measures and linking them to mechanisms of gait dysfunction.

3.2 Introduction
Symmetry is a gait characteristic that is increasingly reported, particularly after stroke. Symmetry may provide important insight about the quality of walking, unique from more
conventional measures such as velocity, and may have a role in guiding the clinician’s treatment decisions\textsuperscript{5}. Despite the potential importance, there is no commonly accepted standard for either the method used to calculate gait symmetry or the gait parameter to assess. The purpose of the present work is to compare the properties of commonly used expressions of gait symmetry with the goal of achieving a recommendation for standardized practice. Note that the current focus is on spatiotemporal characteristics of gait as they have been most commonly used, even though some studies have advocated for the use of kinematic and/or kinetic indices\textsuperscript{37,135}.

There are two components of a symmetry measure to be considered: 1) the equation to calculate symmetry and 2) the spatiotemporal gait parameter used in the equation. There are two types of symmetry equations: 1) a ratio\textsuperscript{14,22,45,52,53,64,123,136-138} and 2) an index or difference calculation\textsuperscript{25,37,49,139}. In addition, there are two variations of the ratio method. One variation is a log transformation of the ratio of right and left swing times\textsuperscript{140}. The second variation is the symmetry angle, which is formed by the x-axis and the vector created by plotting the right and left values of a discrete gait parameter\textsuperscript{141}.

As noted, the other essential component of a symmetry measure is the gait parameter used to compute the symmetry index or ratio. The most common parameters used are step length, swing time, stance time, double support time and single support time\textsuperscript{14,22,25,37,49,52,53,64,123,136-139}. Symmetry calculations based on different spatiotemporal gait parameters may yield unique information about the control of walking. For example, asymmetry in stance times versus swing times, while there is likely some degree of association, may provide insight into different challenges in control
of each phase. Therefore, in addition to comparing the method of calculation, the current study also compares spatiotemporal gait parameters analyzed for symmetry.

To the best of our knowledge, no other study has compared different equations, using spatiotemporal values, within the same patient group. The current study examined associations both across various symmetry measures and between symmetry measures and velocity (a well established gait measure) in order to determine if the measures provided unique information about characteristics of gait symmetry in a group of community-dwelling, ambulatory individuals with stroke. Four equations were analyzed: 1) symmetry ratio, 2) symmetry index, 3) log-transformed symmetry ratio and 4) symmetry angle. In addition, we compared five gait parameters: step length, swing time, stance time, double support (DS) time and the intra-limb ratio of swing:stance time (SW/ST). This study aimed to make a recommendation regarding the most suitable candidate for standardization. The potential clinical benefits of the various symmetry measures are also discussed.

3.3 Methods

3.3.1 Participants

Participants were recruited as they presented to two sites: the Toronto Rehabilitation Institute and the Sunnybrook Health Sciences Centre for Stroke Recovery. Inclusion criteria were 1) unilateral stroke (hemorrhagic or ischemic) and 2) independent walking (defined as the ability to walk 10m without supervision). Participants were excluded if they were unable to follow verbal requests. A total of 161 individuals with stroke
participated. The mean (SD) age was 62.7 (13.6) years and time post-stroke for the group was 23.7 (32.1) months. Fifty-five participants (34.2%) were women and 77 (47.8%) of the group had right-side hemiparesis. A convenience sample of 21 healthy participants was recruited to establish confidence intervals for ‘normal’ symmetry. The mean age for the control group was 27.8 (5.6) years and 15 participants (71.4%) were women. Note that previous work demonstrated no age related differences for indices of symmetry\(^5\).

This study was approved by the Research Ethics Boards at the Centre for Stroke Recovery (Sunnybrook Health Sciences Centre) and the Toronto Rehabilitation Institute (University Centre). All participants provided written informed consent.

### 3.3.2 Gait Measurement

Stroke and healthy participants performed three trials of walking at their preferred speed, across a level 10m walkway which included a pressure sensitive mat in the middle. Spatiotemporal parameters of gait were measured using the mat (GaitRite\(^\text{TM}\), CIR Systems, Clifton, NJ). The GaitRite\(^\text{TM}\) mat is 366cm in length and 81cm in width and contains a grid of 48 by 288 sensors (total of 13824 sensors) arranged 1.27 cm on center. Data were sampled at 30Hz.

### 3.3.3 Data and Statistical Analysis

Calculation of spatiotemporal parameters was performed using the GaitRite\(^\text{TM}\) system. All values were averaged over the three trials for each individual and average data were used for calculation of the different indices of gait symmetry. Spatiotemporal parameters (V), including step length, swing time, stance time, DS time and SW/ST were each used in the following equations (length is in centimetres and time is in seconds):
1. **Symmetry Ratio (ratio):**  \[ \text{Ratio} = \frac{V_{\text{paretic}}}{V_{\text{non-paretic}}} \]

2. **Symmetry Index (SI):**  \[ \text{SI} = \left[ \frac{V_{\text{paretic}} - V_{\text{non-paretic}}}{0.5 (V_{\text{paretic}} + V_{\text{non-paretic}})} \right] \times 100\% \]

3. **Gait Asymmetry (GA):**  \[ \text{GA} = \left| 100 \times \ln \left( \frac{V_{\text{paretic}}}{V_{\text{non-paretic}}} \right) \right| \]

4. **Symmetry Angle (SA):**  \[ \text{SA} = \left( 45^\circ - \arctan \left( \frac{V_{\text{paretic}}}{V_{\text{non-paretic}}} \right) \times 100\% \right) / 90 \]

### 3.3.4 Comparison of Symmetry Measures between Healthy and Stroke Groups

All statistical analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, NC). The distributions, mean and standard deviation (SD) of all twenty symmetry measures were calculated for stroke and healthy participants. Unpaired t-tests were used to compare the groups. A Bonferroni correction was used to adjust for the large number of comparisons. A level of P < 0.002 was considered statistically significant.

### 3.3.5 Symmetry Classification of Individuals with Stroke

To define normative symmetry values, the 95% confidence interval (CI) was taken for each symmetry measure calculated for the healthy group. Each stroke participant was identified as asymmetric, based on each of the 20 symmetry values calculated, if the measure fell outside the CI.

### 3.3.6 Comparison of Symmetry Measures within the Stroke Group

Comparison of the various symmetry measures, within the stroke group, was made from two perspectives: 1) the association between measures and 2) the relationship of the symmetry measure to preferred gait velocity, using Pearson correlations. For the association between symmetry measures, 12 correlations were performed across the symmetry equations, within a gait parameter (Bonferroni corrected P level < 0.004) and
20 correlations were performed across the gait parameters, within each symmetry equation (Bonferroni corrected P level < 0.002). For the association of symmetry measure to gait velocity, five correlations were performed (Bonferroni corrected P level < 0.01).

3.4 Results

3.4.1 Comparison of Symmetry Measures between Healthy and Stroke Groups

All participants performed the walking task without physical support or a gait aid. Twelve participants wore an ankle-foot orthosis or splint during testing. The mean (SD) preferred velocity of the group was 72.30 (33.32) cm/s. Compared to the healthy group, the stroke participants had greater average asymmetry for all four symmetry equations using step length, swing time, stance time and SW/ST (p<0.002). There were no significant differences between the two groups in the four DS time symmetry measures (Table 3.1).

As expected, all measures in the patient group reflected a skewed distribution indicating the presence of gait asymmetry compared to the healthy participants (skewness ranged across patients from -3.42 to 4.76 and across healthy individuals from -0.51 to 1.90). The distributions also highlighted variability in the direction of asymmetry across individuals (i.e. more time spent on the paretic or non-paretic limb). Ratio values less than 1.0 and SI and SA values less than 0.0 indicate more time spent on the non-paretic limb. The percentage of asymmetric individuals who spent more time on (or, in the case of step length, took a longer step with) the paretic limb was: 48.8% for step length, 69.1% for swing time, 28.6% for stance time, 55.6% for DS time and 68.6% for
Table 3.1 Mean (SD) values of the amplitude of all 20 symmetry measures for the healthy controls (n=21) and stroke participants (n=161) calculated with 4 equations: ratio, symmetry index (SI), gait asymmetry (GA) and symmetry angle (SA) using 5 spatiotemporal gait parameters: step length, swing time, stance time, double support (DS) time and the intra-limb ratio of swing to stance time (SW/ST). Also included are the upper CI boundary values for the symmetry measures of the healthy controls and the number of stroke participants identified as asymmetric with respect to this boundary. Significant differences in group mean values for healthy and stroke participants are indicated by an asterisk (*) (p<0.002).

<table>
<thead>
<tr>
<th></th>
<th>Healthy Participants</th>
<th>Stroke Participants</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Upper CI Boundary</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Step length ratio*</td>
<td>1.02 (0.02)</td>
<td>1.06</td>
<td>1.13 (0.20)</td>
</tr>
<tr>
<td>Swing time ratio*</td>
<td>1.02 (0.02)</td>
<td>1.06</td>
<td>1.24 (0.34)</td>
</tr>
<tr>
<td>Stance time ratio*</td>
<td>1.02 (0.03)</td>
<td>1.08</td>
<td>1.09 (0.10)</td>
</tr>
<tr>
<td>DS time ratio</td>
<td>1.02 (0.01)</td>
<td>1.04</td>
<td>1.02 (0.04)</td>
</tr>
<tr>
<td>SW/ST ratio*</td>
<td>1.04 (0.04)</td>
<td>1.12</td>
<td>1.38 (0.53)</td>
</tr>
<tr>
<td>Step length index*</td>
<td>2.44 (1.62)</td>
<td>5.63</td>
<td>10.99 (13.63)</td>
</tr>
<tr>
<td>Swing time index*</td>
<td>2.14 (1.81)</td>
<td>5.69</td>
<td>18.61 (21.49)</td>
</tr>
<tr>
<td>Stance time index*</td>
<td>2.29 (2.64)</td>
<td>7.46</td>
<td>31.58 (74.29)</td>
</tr>
<tr>
<td>DS time index</td>
<td>1.70 (1.18)</td>
<td>4.01</td>
<td>2.26 (3.65)</td>
</tr>
<tr>
<td>SW/ST index*</td>
<td>4.21 (3.79)</td>
<td>11.63</td>
<td>26.12 (28.61)</td>
</tr>
<tr>
<td>Step length GA</td>
<td>2.44 (1.62)</td>
<td>5.63</td>
<td>11.11 (14.07)</td>
</tr>
<tr>
<td>Swing time GA*</td>
<td>2.14 (1.81)</td>
<td>5.69</td>
<td>19.03 (22.49)</td>
</tr>
<tr>
<td>Stance time GA*</td>
<td>2.29 (2.64)</td>
<td>7.46</td>
<td>8.36 (8.86)</td>
</tr>
<tr>
<td>DS time GA</td>
<td>1.70 (1.18)</td>
<td>4.01</td>
<td>2.26 (3.67)</td>
</tr>
<tr>
<td>SW/ST GA*</td>
<td>4.21 (3.80)</td>
<td>11.63</td>
<td>27.15 (30.72)</td>
</tr>
<tr>
<td>Step length SA*</td>
<td>0.78 (0.52)</td>
<td>1.79</td>
<td>3.46 (4.22)</td>
</tr>
<tr>
<td>Swing time SA*</td>
<td>0.68 (0.58)</td>
<td>1.81</td>
<td>5.81 (6.58)</td>
</tr>
<tr>
<td>Stance time SA*</td>
<td>0.73 (0.84)</td>
<td>2.37</td>
<td>2.64 (2.78)</td>
</tr>
<tr>
<td>DS time SA</td>
<td>0.54 (0.38)</td>
<td>1.28</td>
<td>0.72 (1.16)</td>
</tr>
<tr>
<td>SW/ST SA*</td>
<td>1.34 (1.20)</td>
<td>3.70</td>
<td>8.05 (8.60)</td>
</tr>
</tbody>
</table>
SW/ST. Although the direction of asymmetry is important (particularly in the clinical setting) we focused on the amplitude of symmetry to compare features of the symmetry measures in the subsequent analyses. In the case of ratio values less than 1.0, the inverse of the value was used in statistical analysis. For negative SI and SA values, the absolute values were used.

3.4.2 Symmetry Classification of Individuals with Stroke

The number of stroke individuals classified as asymmetric by each measure is summarized in Table 3.1. The four symmetry equations were compared, within the five gait parameters, using 2X2 tables to establish the degree to which they discriminated symmetrical and asymmetrical stroke patients. A discordant pair denoted individuals identified as asymmetric (or symmetric) by the ratio and symmetric (or asymmetric) by the SI, GA and SA equations. Note that in most cases, with the exception described below, the SI, GA and SA equations behaved identically in terms of symmetry classification. Therefore, only the ratio equation was compared to each of SI, GA and SA in the 2x2 tables. The equations were nearly identical in discriminative ability as indicated by the small number of discordant pairs: n=2 or less for step length, SW/ST, swing time and DS time comparisons. The stance time symmetry comparisons produced a greater number (n=22, 13.6%) of discordant pairs. Only in stance time symmetry comparisons did SI, GA and SA classification behaviour differ. In this case, n=20 (12.4%) individuals were identified as asymmetric by SI and symmetric by GA and SA.

3.4.3 Comparison of Symmetry Measures within the Stroke Group

3.4.3.a. Associations between Symmetry Equations:
Correlation analyses across the different equations, within each gait parameter revealed that all symmetry equations were highly and significantly associated. Coefficients ranged from 0.99 to 1.0 (p<0.004) for step length, 0.97 to 1.0 (p<0.004) for swing time, 0.99 to 1.0 (p<0.004) for DS time and 0.97 to 1.0 (p<0.004) for SW/ST. The four stance time symmetry measures were also significantly correlated but the coefficients were smaller ranging from 0.36 to 1.0 (p<0.004).

3.4.3.b. Associations between Gait Parameters
The greatest variation came from differences in the gait parameters used rather than the symmetry equations. DS time was not significantly correlated with any of the other gait parameters within any of the symmetry equations. Within all four equations, SW/ST was, not surprisingly, significantly correlated with swing time and stance time. Coefficients ranged across comparisons of parameters from 0.55 to 0.99 (p<0.002). Step length was significantly correlated to swing time, stance time and SW/ST within all symmetry equations; however, the coefficients were smaller (from 0.34 to 0.51, p<0.002). The only exception to this pattern was the stance time SI and step length SI which were not significantly correlated.

3.4.3.c. Relationship between swing time and stance time symmetry
In light of similarities between the different symmetry equations the remaining analysis was restricted to the ratio equation. The swing time and stance time symmetry ratios were
significantly correlated (0.81, p<0.001) (Figure 3.1). However, we investigated this relationship further since they represent different phases of the gait cycle with different requirements of the musculoskeletal and neurological systems. In Figure 3.1, there are four individuals with swing time symmetry >2.0 who appear to fall outside the general linear trend. These four individuals had a significantly slower gait velocity and significantly larger step length, swing time, stance time and SW/ST symmetry ratios compared to the remaining group (Table 3.2). There were no group differences, between the four individuals and the remaining group, in age, months post-stroke or DS time symmetry ratio. A comparison of the discriminative properties of swing time and stance time ratios (as performed above) revealed the greatest number (n=36, 22.4%) of discordant pairs (Table 3.3).
Table 3.2 Mean (SD) values for gait velocity, step length, swing time, stance time, double support (DS) time, and intra limb swing: stance (SW/ST) symmetry ratios for the outliers of the swing time and stance time symmetry relationship and the rest of the stroke group. Significant differences in group mean values for outliers and remaining stroke group are indicated by an asterisk (*) (p<0.001).

<table>
<thead>
<tr>
<th></th>
<th>Stroke Group (n=157)</th>
<th>Outliers (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>62.76 (13.73)</td>
<td>59.57 (12.30)</td>
</tr>
<tr>
<td>Months Post-stroke</td>
<td>23.45 (32.06)</td>
<td>34.63 (35.29)</td>
</tr>
<tr>
<td>Females</td>
<td>53 (33.8%)</td>
<td>2 (50%)</td>
</tr>
<tr>
<td>Right hemiparetic</td>
<td>75 (47.8%)</td>
<td>2 (50%)</td>
</tr>
<tr>
<td>Gait velocity (cm/s)</td>
<td>73.38 (32.31)</td>
<td>19.16 (10.31)</td>
</tr>
<tr>
<td>Step length ratio*</td>
<td>1.12 (0.16)</td>
<td>1.67 (0.59)</td>
</tr>
<tr>
<td>Swing time ratio*</td>
<td>1.21 (0.26)</td>
<td>2.59 (0.50)</td>
</tr>
<tr>
<td>Stance time ratio*</td>
<td>1.09 (0.10)</td>
<td>1.28 (0.15)</td>
</tr>
<tr>
<td>DS time ratio</td>
<td>1.02 (0.04)</td>
<td>1.04 (0.07)</td>
</tr>
<tr>
<td>SW/ST ratio*</td>
<td>1.34 (0.43)</td>
<td>3.29 (0.61)</td>
</tr>
</tbody>
</table>

Table 3.3 Summary of stroke participants classified as asymmetric or symmetric in swing time and stance time with respect to a 95% confidence interval around the mean swing time and stance time symmetry ratios of 21 healthy adults.

<table>
<thead>
<tr>
<th>Stance Time Symmetry Ratio</th>
<th>Swing Time Symmetry Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symmetric</td>
</tr>
<tr>
<td>Symmetric</td>
<td>63</td>
</tr>
<tr>
<td>Asymmetric</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>64</td>
</tr>
</tbody>
</table>

3.4.3.d. Relationship of Symmetry Measures to Gait Velocity

The step length, swing time, stance time and SW/ST symmetry ratios all had a significant negative association with gait velocity. The correlation coefficients were -0.40, -0.56, -0.48 and -0.55 respectively (p<0.01). DS time symmetry ratio and velocity were not significantly correlated. Between-subject comparisons of gait velocity and symmetry are
included in Figure 3.2. Although overall there was a strong association between preferred velocity and the symmetry ratios (excluding DS time ratio) this was most distinguished for those individuals with a much slower velocity (approximately <60 cm/s.)

3.5 Discussion

This study compared different expressions of gait symmetry used in the literature. Our analysis revealed that the individual equations did not appear to provide any unique differences or contributions to distinguish stroke patients. In contrast, the most important factor was the gait parameter used in the symmetry equation.

3.5.1. Recommendation: The Most Appropriate Symmetry Equation

The four equations were similar in their distribution, highly correlated, and strikingly similar in discriminative ability. Therefore, for the analysis of the current patient data set, it appears that no one equation has a unique advantage over another. However, the ratio equation may be easier to interpret. For example, an individual with a swing ratio of 2.0 has a paretic swing duration twice as long as the non-paretic swing duration. The same hypothetical individual would have a swing SI of 65: a value for which the clinical implications are not immediately clear. Therefore, on the basis of potential clinical utility, we recommend the ratio equation as a candidate for standardization.
Figure 3.2 A between-subject comparison of individuals with stroke, illustrating the significant negative relationship (p<0.001) between preferred gait velocity and (a) step length symmetry (r=-0.40), (b) swing time symmetry (r=-0.56), (c) stance time symmetry (r=-0.48) and (d) SW/ST symmetry (r=-0.55) ratios. Note that these relationships are more clearly defined for those individuals with a slower velocity. In contrast the relationship between velocity and (e) the DS time symmetry ratio was not significant.
There is one caveat to using a ratio which uses the value of 1.0 as “perfect” symmetry. For clinical purposes, a ratio with the paretic gait parameter in the numerator is useful since the direction of asymmetry is indicated by the value itself. However, for statistical analyses, we recommend that the numerator should always be the greater of the two values regardless of the paretic side so that results are not skewed by values less than 1.0. Information about the direction of asymmetry should be retained with a sign convention (e.g. a positive/negative sign to indicate favouring of the paretic/non-paretic limb respectively).

3.5.2 Recommendation: The Most Appropriate Spatiotemporal Gait Parameter

In contrast to the equations, the five gait parameters had varying relationships. DS time was not related to gait velocity or any other gait parameter, within any of the four equations, suggesting it may provide unique information about a patient’s gait. However, DS time symmetry measures identified the fewest asymmetric individuals and the mean values did not differ significantly from the healthy group, indicating that few stroke patients are asymmetric in DS time. Therefore, we do not recommend this gait parameter to distinguish individuals within this patient population.

Swing time, stance time and SW/ST were highly correlated. Step length was also correlated with these temporal parameters, but the coefficients were smaller. In addition, each of these symmetry ratios had a negative linear relationship with velocity that was more clearly defined at slower velocities (<60cm/s), which coincides with our previous work.\textsuperscript{5} Again, the relationship was weakest for step length symmetry suggesting it may provide distinct information from the remaining temporal symmetry ratios.

Balasubramanian and coauthors propose the step length ratio can be used in the clinical
setting to evaluate the propulsive force generated by the paretic leg. In addition to step length symmetry, our results suggest there is merit in analyzing a temporal parameter for symmetry.

Previous investigators recommended the use of swing time symmetry in the stroke population because it coincides with single limb stance time: a significant challenge for the paretic limb and an important determinant of gait. While the current analysis supports this recommendation, the inclusion of stance time symmetry would afford additional insight. Although our analysis revealed a close linear relationship between the two ratios, it also highlighted four outliers from this relationship and thirty-six individuals who were symmetrical in one gait phase (i.e. swing or stance) but asymmetrical in the other. Although the clinical significance is not immediately clear, one possibility is that the two symmetry ratios are related to different aspects of gait control. For example, a larger swing time asymmetry could indicate insufficient power generated to swing the paretic limb quickly or increased time required to control foot placement. On the other hand, a greater asymmetry in stance time (which includes both single and DS times) could be related to balance control issues leading the patient to shorten paretic stance time. Wall and Turnbull noted the importance of examining the extent of asymmetry as well as its location within the gait cycle in order to design a gait rehabilitation program tailored to the deficits of an individual patient. We believe that this premise along with the current results warrant further investigation into the determinants of stance time and swing time asymmetry.
3.6 Conclusion

In conclusion, no symmetry equation demonstrated a clear advantage in terms of distribution or discriminative ability. However, the ratio method affords the advantage of ease of interpretation. The most useful gait parameters are step length, swing time and stance time. Examining both swing and stance time symmetry ratios within an individual may provide a more complete picture of their gait pattern. Future work should focus on the determinants of swing time and stance time asymmetry as well as the reliability and validity of the symmetry indices. In addition, future studies should compare such spatiotemporal indices of post-stroke gait with kinematic\textsuperscript{135} or kinetic\textsuperscript{37} indices to establish the degree of association or discordance and continue to advance the development of a standardized measurement approach for post-stroke symmetry.
4.0 Differences in gait symmetry and velocity after stroke: a cross sectional study from weeks to years after stroke

4.1 Abstract

The conventional view is that gait dysfunction improves over the first three to six months post-stroke and then plateaus. However, there is little information about the status of gait years after a stroke. Information about long-term changes in mobility, using global indices of function, provides some evidence of decline after rehabilitation. A limitation of such studies is that global indices of mobility do not reveal more specific changes in walking competency and underlying gait-specific impairment. The current study used a cross-sectional design with gait-specific measures (velocity and gait symmetry) to investigate the possibility of deterioration in gait in the long term after stroke. The aim of this study was to determine if gait velocity and gait asymmetry are worse in the later stages post-stroke. Data were abstracted from an ongoing standardized database that contains clinical assessments and spatiotemporal gait analyses for individuals with stroke. Velocity and three symmetry ratios (swing time, stance time and step length) were calculated for each individual who were then assigned to one of the five following time post-stroke groups: 0-3, 3-12, 12-24, 24-48 and >48 months post stroke. Mean swing time, stance time and step length asymmetry values demonstrated a systematic linear trend over time post-stroke while velocity, neurologic deficit and lower extremity motor impairment did not. The quality of gait control, as measured by gait symmetry, appears to be worse in the later stages of stroke. In contrast, gait velocity, neurologic deficit and lower limb motor impairment did not exhibit this same pattern. These results suggest dissociation between quantitative measures of gait control (symmetry) and gait capacity.
(velocity) indicating they measure independent features of post-stroke gait. A longitudinal study is warranted to further investigate the potential decline in gait control in the long term post-stroke.

4.2 Introduction

Stroke is associated with many impairments, of which, walking dysfunction is the most commonly reported limitation\(^2\) and one that can profoundly impact independence, quality of life and participation\(^{88}\). The conventional view is that gait improves over the first three to six months post-stroke and then plateaus\(^{19,20,81,133,142}\). Some rehabilitation interventions for chronic stroke patients (>1 year post) have produced gains in the level of independence, walking velocity and distance walked\(^{115,119,143,144}\). However, these gains are sometimes lost at follow-up three to nine months later\(^{115,144}\). This inability to maintain gains after the period of active rehabilitation may be attributed to two factors: 1) the benefits of rehabilitation may be dependent on continued use of the paretic limb and/or 2) the persisting limitations in gait after stroke (e.g. increased energy cost\(^{60}\), challenges to balance control\(^5\), increased risk of musculoskeletal injury to the non-paretic lower extremity (LE)\(^5\) may lead an individual to restrict activity (in spite of a capacity for independent walking) thereby leading to the underlying continued decline in mobility post-stroke suggested by Wade and coauthors\(^{115}\).

There is little information specific to long-term changes in post-stroke gait. Previous studies have relied on global indices of mobility such as the Motor Assessment Scale (MAS) and the Rivermead Mobility Index (RMI). These ordinal measures contain a few
test items (one and five respectively) that directly address walking at the functional level, but do not reveal more specific post-stroke changes in walking competency (e.g. capacity for forward progression, symmetry of the gait pattern). Nevertheless, studies using these measures provide some evidence of decline post-stroke after rehabilitation. Langhammer and coauthors found a decline in MAS scores at one year post-stroke and further decline at four years post-stroke. In contrast, two studies using the RMI found no change in mobility status over the first and second years post-stroke. However, while RMI did not change over time when averaged across the entire group, a subset of individuals did exhibit a decline in mobility (12.2% and 42.6% of the two study groups respectively).

While mobility measures such as the MAS and RMI are useful to indicate an individual’s level of function, they are unlikely to be sensitive to persisting gait-specific challenges associated with stroke. Although improved function is the overall aim of rehabilitation, the interventions are targeted at the level of gait-related impairments and therefore these should be measured directly.

Two gait-specific parameters relevant to the stroke population are velocity and symmetry. Velocity is a widely used measure of gait performance and can differentiate levels of disability in the stroke population. Velocity can be viewed as a measure of the capacity of walking. In this respect, ‘capacity’ refers to the ability to achieve a specific walking speed. An alternative index of capacity might include distance walked (e.g. 6 minute walk test). In contrast, symmetry provides a measure of the parallels between the two LEs so that inter-limb ratios of step length, swing time and stance time provide some insight.
to the underlying control of gait\textsuperscript{96,145}. It is important to include measures of both ‘capacity’ and ‘control’ since there are likely times when the two classes of measures are not strongly associated (e.g. individuals exhibiting very low walking speed but normal symmetry)\textsuperscript{5,52,146}. Importantly, measures such as gait velocity and symmetry are responsive to a variety of rehabilitation interventions in the short-term\textsuperscript{130-132,147,148} but little is known about how these parameters might change in the long-term, once rehabilitation is complete. A small study (n=8) previously revealed that the post-stroke asymmetrical pattern was accentuated over 10 years while no differences in velocity were found\textsuperscript{149}. The current study used a cross-sectional design to extend these earlier observations and to investigate the potential for significant deterioration in gait over the long term post stroke. The hypothesis was that there would be a progressive, linear trend in gait over time post stroke. This would be evidenced by a linear decrease in gait velocity and a linear increase in gait asymmetry (i.e. step length, swing time and stance time symmetry ratios).

### 4.3 Methods

Data were abstracted from an ongoing standardized database that includes individuals with stroke recruited at two institutions: the Toronto Rehabilitation Institute and the Centre for Stroke Recovery at the Sunnybrook Health Sciences Centre. All of the original studies were approved by the Research Ethics Boards at Sunnybrook Health Sciences Centre and Toronto Rehabilitation Institute. All participants provided written informed consent.
Participants were selected from this database if they had sustained a first occurrence of a unilateral stroke (hemorrhagic or ischemic) and had completed an over-ground, preferred-pace walking task without assistance or a gait aid. Some participants had more than one visit recorded in the database. In these cases, a single visit was randomly selected for each individual. Overall a total of 172 participants were included in the present analysis.

4.3.1 Measurements

The database contained data from clinical and laboratory gait assessments. 

*Clinical Assessment:* The clinical assessment consisted of two stroke-specific measures: the National Institutes of Health Stroke Scale (NIHSS) and the Chedoke McMaster Stroke Assessment (CMSA). The NIHSS is a measure of stroke-related neurologic deficit and the reliability and validity of this measure have been established\(^{150}\). The leg and foot dimensions of the CMSA (each measured with a 7-point scale) were used as a measure of motor impairment. Smaller scores indicate greater motor impairment. The CMSA has good intra- and inter-rater reliability as well as good concurrent validity with the Fugl-Meyer\(^ {151,152}\).

*Spatiotemporal Gait Measures:* Spatiotemporal parameters of gait were measured using a pressure sensitive mat (GaitRite, CIR Systems, Clifton, NJ). The GaitRite mat is 366cm in length and 81cm in width and contains a grid of 48 by 288 sensors (total of 13824 sensors) arranged 1.27 cm on center. The system records footfalls by the location of activated sensors and the time of activation/deactivation. Data were sampled at 30Hz and stored in a personal computer that calculated spatial and temporal parameters using
application software. Participants walked across a level walkway over the pressure sensitive mat at their preferred, comfortable speed. The participant began and stopped walking least 150cm before and after the mat so as to ensure steady-state gait throughout the. Three walking trials were recorded and stored for offline analysis.

4.3.2 Data and Statistical Analysis

Gait symmetry calculations: The output from the GaitRite application software was exported as a text file and opened in a spreadsheet using Microsoft Office Excel 2003 for further calculations. All spatiotemporal values were averaged over the three walking trials. Three gait symmetry measures (two temporal and one spatial) were calculated using the following equations with the left and right temporal values that were averaged over the three walking trials (time was reported in seconds and length was reported in centimetres):

Temporal symmetry:

i. Swing time symmetry = larger swing time/ smaller swing time

ii. Stance time symmetry = larger stance time /smaller stance time

Spatial symmetry:

iii. Step length symmetry = larger step length / smaller step length

Time post-stroke groups: In order to determine differences in gait characteristics and motor impairment between individuals at different stages post-stroke, participants were grouped according to months post-stroke at the time of the visit recorded in the database. Participants were assigned to one of the five following groups: 0-3, 3-12, 12-24, 24-48 and >48 months post stroke.
Statistical analyses: All statistical analyses were performed using SAS 9.1 (SAS Institute Inc., Cary, NC). One-way ANOVAs were used to compare the five time groups on age, gender and hemiparetic side. One-way ANOVAs were also computed on swing time, stance time and step length symmetry measures, velocity, NIHSS and CMSA leg and foot scores. To test the study hypothesis that gait asymmetry increases and gait velocity decreases with the stage post-stroke, contrast analyses were computed on the three symmetry measures and velocity across the 5 time groups to look for significant linear trends in the data. This analysis was also carried out for NIHSS and CMSA foot and leg scores to check for recruitment bias (i.e. increased likelihood of recruiting individuals with greater impairment at later stages post-stroke.) Rank transformations were performed prior to analysis on data that were not normally distributed as well as on ordinal data (i.e. NIHSS, CMSA). Post hoc analysis was conducted (Tukey) to assess the specifics of group differences revealed by the ANOVA that were not consistent with the prior hypothesized linear trends.

4.4 Results

4.4.1 Participants

The database contained data from 194 individuals. The number of individuals excluded and the reasons for exclusion were as follows: 8 because of a second occurrence of stroke, 2 because gait analysis was completed with a cane, 6 because the exact date of stroke was missing and 6 because they did not have a confirmed diagnosis of stroke. Of the remaining 172 individuals, 39 had more than one visit recorded in the database. A single visit was randomly selected for each of these 39 individuals. In total, 172 visits
(from 172 unique participants) were used in the analysis. The mean (SD) age of the group was 63.2 (13.2) years and the mean time post-stroke was 23.2 (31.1) months. Sixty-one participants (35%) were women and 83 (48%) exhibited right hemiparesis. The mean values of gait measures for the entire group were as follows: velocity 72.92 (32.89) cm/s, swing time symmetry 1.25 (0.39), stance time symmetry 1.09 (0.10) and step length symmetry 1.13 (0.25). The mean NIHSS for the entire group was 2.6 (2.3) and mean CMSA leg and foot scores were 5.0 (1.4) and 4.8 (1.5) respectively. The 5 post-stroke groups were not significantly different in mean age, proportions of men and women or proportions of individuals with left and right hemiparesis. A summary of demographic variables for the entire group and each of the 5 post-stroke groups is included in Table 4.1.

**Table 4.1** Summary of mean (SD) values for demographic data for the entire study group as well as each of the 5 post-stroke groups

<table>
<thead>
<tr>
<th></th>
<th>Whole group (n=172)</th>
<th>0-3 months (n=63)</th>
<th>3-12 months (n=27)</th>
<th>12-24 months (n=26)</th>
<th>24-48 months (n=27)</th>
<th>&gt;48 months (n=29)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age (y)</strong></td>
<td>63.2 (13.2)</td>
<td>65.2 (13.1)</td>
<td>63.4 (10.6)</td>
<td>66.4 (11.5)</td>
<td>61.2 (16.1)</td>
<td>57.5 (13.1)</td>
</tr>
<tr>
<td><strong>% of Females</strong></td>
<td>35</td>
<td>35</td>
<td>37</td>
<td>39</td>
<td>22</td>
<td>45</td>
</tr>
<tr>
<td><strong>Time post stroke (months)</strong></td>
<td>23.2 (31.0)</td>
<td>1.2 (0.8)</td>
<td>7.1 (3.0)</td>
<td>17.4 (3.1)</td>
<td>32.5 (7.4)</td>
<td>82.7 (26.7)</td>
</tr>
<tr>
<td><strong>% right hemiparesis</strong></td>
<td>48</td>
<td>40</td>
<td>52</td>
<td>54</td>
<td>48</td>
<td>59</td>
</tr>
<tr>
<td><strong>% of whole group</strong></td>
<td>-</td>
<td>37</td>
<td>16</td>
<td>15</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

4.4.2 Differences in Gait Symmetry

The mean swing time, stance time and step length symmetry values for each post-stroke group are included Figure 4.1. One-way ANOVAs computed on each symmetry measure
Figure 4.1 Group mean symmetry values for each time group demonstrating a significant linear trend over time post-stroke. (a) Swing time symmetry ($F=13.26, p<0.01$) (b) stance time symmetry ($F=9.27, p<0.01$) and (c) step length symmetry ($F=6.06, p=0.01$) (Note the y-axis begins at 1.0).
revealed a significant main effect for post-stroke group (swing: F=3.46, p<0.01, stance: F= 2.92, p=0.02, step: F= 3.16, p=0.02). Contrast analysis revealed a linear trend in swing time (F=13.29, p<0.01), and stance time (F=9.27, p<0.01) symmetry values over the 5 post-stroke groups. Visual inspection of the data revealed a systematic increase in swing and stance time symmetry measures across the 5 groups. Contrast analysis for step length symmetry was also significant (F=6.05, p=0.01) however visual analysis of the data included in Figure 1c did not reveal a pattern of systematic increase in step length asymmetry across the groups, as seen in Figures 1a and 1b. Furthermore, a post hoc Tukey analysis revealed a significant difference in step length symmetry between the 3-12 months and 24-48 months post-stroke groups. Mean step length symmetry was lower in the 3-12 months group (also noted Figure 4.1).

4.4.3 Differences in Gait Velocity

The mean gait velocity for each group is included in Figure 4.2. Note that the average velocity for the entire group, 72.92 (32.89) cm/s, is considerably lower compared to reported values for healthy adults aged 60 to 69 years (139.5 (20.9) cm/s for men and 129.6 (21.3) cm/s for women). In contrast to symmetry, the one-way ANOVA revealed no significant main effect of time (F=1.38, p=0.24) and contrast analysis revealed no significant linear trend in gait velocity (F=1.17, p=0.28). It is noteworthy that while this difference in the group trends between velocity and symmetry reveals a potentially important dissociation over time, it does not conflict with the more global association between symmetry and velocity as reported in previous studies.
Pearson correlations, using the entire study group (n=172), revealed a significant negative relationship between velocity and all three symmetry measures (swing: $r=-0.54$, stance: $r=-0.48$ step: $r=-0.46$, all $p<0.01$).

4.4.4. Differences in Neurologic Deficit and Motor Impairment

The mean NIHSS scores for each group are included in Figure 4.3. One-way ANOVA revealed a main effect for post-stroke group ($F=4.56$, $p<0.01$) However, no significant linear trend was found with contrast analysis ($F=2.6$, $p=0.11$). A post hoc Tukey analysis revealed a significant difference in NIHSS scores between the 0-3 months and 3-12 months post-stroke groups. The mean NIHSS score was lower in the 3-12 months group (also noted in Figure 4.3).
The mean CMSA leg and foot scores for each group are included in Figure 4.4. There was no significant main effect for post-stroke group (F=2.06, p=0.09) and contrast analysis revealed no significant linear trend in CMSA leg scores over the 5 groups (F=2.48, p=0.12). In contrast, one-way ANOVA computed on CMSA foot scores revealed a significant main effect for post-stroke group (F=2.46, p=0.049). However, no significant linear trend was found with contrast analysis (F=3.24, p=0.07). A post hoc Tukey analysis revealed a significant difference in CMSA foot scores between the 3-12 months and 24-48 months post-stroke groups. The mean CMSA foot score was lower in the 24-48 months group (also noted in Figure 4). As mentioned for velocity above, our

**Figure 4.3** Mean NIHSS scores for each time group demonstrating a significant main effect for time (F=4.56, p<0.01) but no significant linear trend (F=2.6, p=0.11). Significant differences between groups are indicated by an asterisk (*).
results are consistent with the more global association between symmetry and motor impairment as reported in previous studies\textsuperscript{5,22,45,56}. Pearson correlations (using the entire study group (n=172)) revealed a significant negative relationship between CMSA leg scores and all three symmetry measures (swing: $r=-0.58$, stance: $r=-0.50$ step: $r=-0.41$, all $p<0.01$) and CMSA foot scores and the symmetry measures (swing: $r=-0.58$, stance: $r=-0.53$ step: $r=-0.41$, all $p<0.01$).

### 4.5 Discussion

This preliminary, cross-sectional analysis indicates that swing time and stance time asymmetry is worse in the later stages post-stroke. In contrast, gait velocity,
neurologic deficit, and motor impairment did not exhibit the same systematic across the stages post-stroke. The current finding of stable gait velocity and worsening gait asymmetry is consistent with previous work by Turnbull and Wall. However, our results differ from a cross-sectional study of 49 individuals with stroke by von Schroeder and colleagues, which found an increase in velocity over the first 12 months post-stroke and a constant pattern of temporal asymmetry (although actual symmetry ratios were not reported). With respect to the von Schroeder et al. work, the current study featured a larger, more gait-impaired study group (i.e. slower and more asymmetric). Therefore, the probability of revealing differences in asymmetry would be greater in the present sample.

Previous work has found that the timing of gait phases (e.g. stance phase, double support phase) in healthy adults is consistent regardless of gender or age. Therefore it is unlikely that the trend for increasing asymmetry and thus the decline in gait control, observed in the current study, can be attributed to increasing age alone. In addition, the absence of differences in velocity among the same individuals contradicts the view that increases in asymmetry are a product of a more general age-related decline in gait performance.

The interpretation of the changes in step length asymmetry is more difficult. Statistically, there was a significant linear trend. However, visual inspection and post-hoc analysis reveals a more complex pattern of increasing step length asymmetry across the stages post-stroke, as compared to the pattern exhibited by both swing and stance time.
asymmetry. Therefore, the present results do not allow for any conclusive statement to be made about how spatial asymmetry may differ between various stages post-stroke.

As mentioned above, gait velocity did not differ across the stages post-stroke. Velocity is more strongly associated with gait phases of the non-paretic LE compared to the paretic LE. This may reflect adaptive behaviours of the non-paretic LE that compensate for the affected LE. It is possible that once behavioural compensations have been developed and refined in the sub-acute period, an individual may not deviate from their post-stroke preferred walking velocity and thus velocity remained constant in the present study. Perhaps of more interest is the apparent dissociation between measures of gait capacity (velocity) and gait control (symmetry). As noted, this dissociation in behaviour, when examined across the stages post-stroke, is independent of the relatively strong association between velocity and symmetry (assessed across all individuals) found in the present and previous work. The difference in the behaviour of these two variables over time may indicate that they measure separate features of post-stroke gait.

It could be argued that in such cross sectional studies, there may have been selection bias: patients with more severe deficits were more likely to be recruited in the later stages post-stroke than patients with less severe impairments. We think this is unlikely a significant concern in the current study since stroke severity as defined by both neurologic deficit (NIHSS) and motor impairment (CMSA) appeared similar across these groups. However, similar to the dissociation between velocity and symmetry, the difference in trends,
across the stages post-stroke, between limb-specific impairment (CMSA) and gait-specific impairment (symmetry) is a potentially important observation.

There is a prevailing clinical belief that gait asymmetry is merely an individual’s compensation for LE motor impairment. Indeed, motor impairment is significantly associated with gait asymmetry as demonstrated in both the present and previous studies\(^5,22,45\). However, it has also been shown that individuals with mild motor impairment (e.g. CMSA scores of 5-7) may exhibit temporal asymmetry\(^5,145\). Therefore, motor impairment alone is unlikely to account for all the variation of gait asymmetry observed in the post-stroke population. The current results further support this assertion. If gait asymmetry is simply a compensation for LE impairment and the two are tightly linked, then the strong, systematic increase in temporal symmetry values would not have been expected since the CMSA scores did not show the same trend. So while there is an underlying association between limb-specific and gait-specific impairment, this association is modest and does not appear to account for group related differences in gait control (symmetry) in the present study. Two possible explanations for this distinction are: 1) measures of limb-specific impairment reflect more general challenges to LE control not specific to the unique control of walking and/or 2) changes over time were specific to the control of walking independent of limb-specific dyscontrol. The current study reinforces the importance of better understanding the link between limb control and gait control. These matters remain important to resolve as they impact greatly on the focus of therapy and would help guide gait rehabilitation interventions.
We believe the asymmetrical gait pattern warrants increased attention both clinically and in research for many reasons. First, the current results demonstrate that gait asymmetry clearly persists and may progresses in the later stages post-stroke. Thus the quality of gait control may diminish in the long-term post-stroke. Second, gait asymmetry is associated with many potential negative consequences (e.g. challenges to balance control, increased energy expenditure, increased risk of musculoskeletal injury to the non-paretic LE, decreased overall activity levels \(^5\)). Third, gait symmetry can serve as a complementary measure of gait control and post-stroke recovery \(^5,52,53\). Fourth, the dissociation between velocity and symmetry in terms of their behaviour across the various stages post-stroke indicates that they each measure a different characteristic of gait and therefore both should be considered when evaluating post-stroke gait.

4.5.1. Implications

It appears that the control of gait may decline in the later stages post-stroke. A prospective, longitudinal study is warranted to investigate this and may also clarify changes in step length symmetry over time. If the current results are supported, then new approaches to post-stroke gait will be needed. Two main lines of inquiry should be pursued. The first area of focus should be identifying characteristics that distinguish individuals who demonstrate a worsening of gait asymmetry from those who do not. It is possible that a symmetry threshold exists, such that individuals below this threshold will maintain their gait pattern, whereas those above it are at risk for further decline after discharge from therapy. A second, related area of focus is the development of new rehabilitation programs that target gait asymmetry. Two approaches are (1) interventions
aimed at bringing gait asymmetry below the theoretical threshold described above and (2) intermittent interventions or ‘check up’ programs that monitor individuals post-stroke at risk for decline in gait control. Gait measurement by these monitoring programs must include quantitative measures more sensitive than global mobility measures (e.g. MAS, RMI). In addition, since it is possible that gait control may decline, independent from gait capacity (velocity), separate measures of gait control, (i.e. temporal and spatial asymmetry) should be included.
5.0 Feasibility of a rehabilitation intervention to influence gait symmetry in
subacute ambulatory stroke patients

5.1 Abstract

Treadmill (TM) training is a popular paradigm since it provides task-oriented training. While there is evidence of change in the capacity for gait (e.g. velocity, endurance) with TM training, evidence of changes in the control of walking is less convincing. For example, gait asymmetry (a measure of gait control) is often considered resistant to rehabilitation interventions. It is likely that some of this resistance to change is due to lack of specificity to influence gait symmetry. We believe a focus on gait symmetry is important because of the potential negative consequences of persisting gait asymmetry after stroke. Therefore, the aim of this study was to investigate the feasibility of a TM training intervention using visual feedback about gait symmetry. The objectives of this study were: 1) to determine if subacute stroke patients could significantly alter their gait symmetry in response to biofeedback and 2) determine if the change in symmetry was accomplished through increased paretic limb use. Eight participants post-stroke, (mean duration since onset 3.2 (1.8) months) ambulated on a TM in a safety harness, for 1 minute bouts under 4 different conditions: 1) baseline (BASE): without visual feedback or special instructions, 2) self-monitored (SELF): verbal instructions to walk symmetrically, 3) visual feedback (FB): with visual feedback about stance time symmetry and 4) dual task (DT): performance of a concurrent cognitive task. Footswitches recorded footfall events and EMG recordings were taken bilaterally from tibialis anterior, medial gastrocnemius, semitendinosus and vastus lateralis. Comparisons of symmetry
ratios and temporal gait parameters were made within participants, between the BASE and the three remaining TM conditions. EMG gait profiles were also compared. Four of 6 participants (for whom data could be analyzed) exhibited significantly different gait symmetry in response to FB. There was inter-individual variation in the strategy used to alter gait symmetry. Gait changes with FB were unique from those exhibited in the SELF and DT conditions. Some stroke participants can significantly change their gait symmetry in response to visual FB indicating that gait asymmetry is responsive to interventions that specifically target this gait parameter. However, individuals did not necessarily produce improved gait symmetry in the intended manner of increased paretic limb use. This issue may be solved by on-line monitoring of gait parameters and modifications to the FB program to make it specific to the paretic limb. Future work should investigate the effectiveness of paretic-limb- specific FB training and the carryover of symmetry training to over-ground gait.

5.2 Introduction

Stroke is the leading cause of adult neurologic disability that affects all aspects of life including activities of daily living, mobility, communication and cognition. Walking is often affected by stroke and improvement of walking function is the goal most often stated by stroke patients. Due to its importance to patients and independent function, walking receives considerable attention in rehabilitation. Despite this, most stroke patients are left with varying degrees of walking dysfunction after discharge from rehabilitation. Post-stroke gait deficits include decreased velocity, reduced cardiovascular fitness and temporal gait asymmetry.
New strategies and interventions to improve post-stroke gait rehabilitation outcomes are continually investigated and reported. Currently, treadmill (TM) training is a popular paradigm since it provides task-oriented training. Task-oriented training is believed to be more effective at improving gait post-stroke than other approaches and TM training has recently been linked to functional reorganization of the cortex\textsuperscript{113,125}. Most post-stroke TM training paradigms focus on improving capacity (e.g. gait velocity and/or cardiovascular fitness) rather than control of walking. TM training in chronic stroke patients produces significant increases in over-ground gait velocity and walking distance (as measured by the 6 minute walk test (6MWT))\textsuperscript{12,13}, improved cardiovascular fitness (as measured by oxygen consumption)\textsuperscript{12,13,124,126} and significantly reduces energy expenditure during gait\textsuperscript{126}. TM training has also been successfully implemented in the subacute stroke population. After TM training, subacute stroke patients require a reduced level of assistance\textsuperscript{9,10}, walk further and faster on the 6MWT\textsuperscript{11} and exhibit increased gait velocity\textsuperscript{9-11}. Clearly gait velocity and endurance are responsive to training.

While there is evidence of change in the capacity for gait, evidence of changes in the control of walking are less convincing. For example, gait asymmetry (a measure of the quality of gait control)\textsuperscript{96,145} is often considered resistant to general gait rehabilitation interventions\textsuperscript{12,14,15}. It is likely that some of this ‘resistance’ to change is due to the fact that few TM training paradigms focus specifically on ameliorating gait asymmetry. Typical TM training parameters that are progressed over the intervention period include treadmill velocity\textsuperscript{9} and aerobic training level (i.e. heart rate reserve)\textsuperscript{12,13,124,126}. Although some studies use temporal gait symmetry as an outcome measure\textsuperscript{11,12} and one subacute
study demonstrated improved symmetry of single support time\textsuperscript{11}, no TM studies examined a training paradigm that specifically trained for improved temporal gait symmetry.

We believe a focus on gait symmetry is important because of the potential negative consequences of persisting gait asymmetry after stroke. The asymmetrical gait pattern is inefficient, poses increased challenges to balance control and may expose the individual to increased risk of musculoskeletal pain and joint degeneration\textsuperscript{5}. There is also evidence that gait asymmetry may worsen over time post-stroke\textsuperscript{149}. In light of the associated negative consequences, asymmetry post-stroke is an important issue to address and considering the potential for asymmetry to worsen over time; it is likely best to address it in the early stages post-stroke.

As mentioned above, the absence of large changes in gait asymmetry with TM training is likely due to the lack of specificity of the training paradigm. While there are no studies that focus specifically on temporal gait symmetry there have been two training approaches that focussed more closely on inter-limb coordination which is linked to temporal symmetry: rhythmic auditory cueing (RAC)\textsuperscript{130,158} and split-belt TM training\textsuperscript{132}. Although these training approaches led to significant changes in gait symmetry, the resultant gait pattern was still significantly asymmetric compared to the range of symmetry values for healthy adults\textsuperscript{132,158}. A recent study used unilateral step training (UST) to specifically train step length/spatial symmetry\textsuperscript{131}. Ten sessions of UST lead to an improvement in step length symmetry but did not improve single limb support/swing
time symmetry\textsuperscript{131}. The results of RAC, split-belt TM training and UST support the concept that stroke patients retain the ability to produce a symmetric gait pattern\textsuperscript{132}. Previous work has demonstrated that temporal asymmetry is more prevalent than spatial asymmetry in the post-stroke population and so we have chosen to focus our training paradigm on influencing the degree of temporal gait asymmetry\textsuperscript{5}.

Biofeedback has been used frequently in the rehabilitation field and there is evidence that both subacute and chronic stroke patients can use biofeedback to alter motor performance. Both visual and auditory biofeedback have been used successfully to train a variety of motor tasks including symmetrical weight distribution in sitting\textsuperscript{159}, standing\textsuperscript{160} and during the sit-to-stand movement\textsuperscript{161}, improving peak paretic plantarflexor power\textsuperscript{162} and step length symmetry\textsuperscript{163} during gait and finally increasing force production by the lower extremity\textsuperscript{164}. There is some evidence that feedback is more effective at improving motor performance than other physiotherapy interventions\textsuperscript{159} and that these improvements are retained at follow up 6-12 weeks later\textsuperscript{159,162}. Biofeedback interventions may also induce cortical reorganization associated with functional improvement\textsuperscript{165}.

The main objective of this study was to investigate the feasibility of a TM training intervention using visual biofeedback about gait symmetry. The primary objective was to determine if subacute stroke patients could significantly alter their gait symmetry in response to biofeedback regarding gait symmetry. TM walking while responding to biofeedback is a form of dual-task (i.e. performing two tasks concurrently). Dual task
effects have been shown to adversely affect postural control and velocity of gait in individuals with stroke\textsuperscript{166,167}. Therefore, in order to investigate potential cognitive-motor interference due to biofeedback, we included a cognitive dual task TM walking trial for comparison. In addition, gait symmetry is often addressed clinically using verbal instructions given to the patient. In order to determine if biofeedback was more effective at inducing changes in gait symmetry that simple instructions we included a TM walking trial in which patients were given verbal instruction to walk more symmetrically.

An important element of interventions aimed at improving gait control (symmetry) is to ensure that increased use of the paretic limb is encouraged instead of compensatory actions by the non-paretic limb\textsuperscript{168}. Therefore a secondary objective of this study was to determine if the change in symmetry was accomplished in the intended manner of increased paretic limb use, specifically, by increasing or decreasing affected gait phase durations to equal that of the unaffected limb. This was assessed in two ways: 1) spatiotemporal gait parameters and 2) EMG gait profiles of 4 lower extremity muscles (tibialis anterior, medial head of gastrocnemius, vastus lateralis and semitendinosus).

5.3 Methods

5.3.1 Participants

Participants were recruited as they presented to the Toronto Rehabilitation Institute. Inclusion criteria were 1) a Chedoke McMaster Stroke Assessment (CMSA) leg score between 3 and 7 and 2) the ability to understand verbal instructions for TM walking tasks. A total of 8 individuals with stroke participated. The mean (SD) age was 60.6
(18.6) years and time post-stroke for the group was 3.2 (1.8) months. 5 participants (62.5%) were women and 4 (50%) individuals had right-side hemiparesis. This study was approved by the Research Ethics Board at the Toronto Rehabilitation Institute. All participants provided written informed consent.

5.3.2 Clinical Measurement

Participants were characterized clinically using standardized, performance-based clinical scales. Motor impairment of the leg and foot were measured using a performance-based measure, the Chedoke-McMaster Stroke Assessment (CMSA). Balance was measured using the Berg Balance Scale (BBS). Both of these measures have established reliability and validity for use with individuals with stroke\textsuperscript{151,152,169}.

5.3.3 Over-ground Gait Measurement

Participants performed three trials of walking at their preferred speed, across a level 10m walkway which included a pressure sensitive mat in the middle. Spatiotemporal parameters of gait were measured using the mat (GaitRite\textsuperscript{TM}, CIR Systems, Clifton, NJ). The GaitRite\textsuperscript{TM} mat is 366cm in length and 81cm in width and contains a grid of 48 by 288 sensors (total of 13824 sensors) arranged 1.27 cm on center. Data were sampled at 30Hz. Key measures of interest were velocity, step length symmetry, swing time symmetry and stance time symmetry. These measures were selected to characterize both the participant’s capacity for gait (velocity) and control of gait (symmetry).

5.3.4 EMG Measurement

EMG recordings were measured using surface electrodes fixed 2cm apart (center to center) along the belly of each lower extremity muscle. Electrode sites were prepared using alcohol and a mild abrasive agent to reduce impedance of the skin. Recordings
were taken from the following muscles bilaterally: tibialis anterior, medial head of gastrocnemius, semitendinosus and vastus lateralis. The reference electrode was placed over the anterior surface of the distal tibia. Each site was checked for cross-talk using manually resisted isometric contraction for each muscle group with the patient seated.

EMG activity was sampled at 1000Hz and signals were amplified (500x), transmitted to an Analog to Digital converter (Noraxon, Scottsdale, AZ) and recorded as a digital signal with MyoResearch XP 1.06.04 (Noraxon, Scottsdale, AZ)

5.3.5 Task Protocol

Participants walked on a TM (Biodex Medical Systems, Shirley, NY) at their preferred speed in a safety harness with pressure sensitive footswitches taped to the soles of their shoes (as mentioned previously). Note that the harness was not used to support any body weight but rather as safety device to prevent the possibility of falling. Footfall events recorded by the footswitches were stored for further off-line analysis. Prior to testing, participants were allowed approximately two to five minutes of practice to determine their preferred speed and to acclimate to the TM. Patients were instructed to select a speed at which they felt comfortable and safe while holding only one TM handrail. After the acclimation process, participants performed 1 minute bouts of TM walking during which time both footswitch and EMG data was sampled. TM walking bouts were performed under the following conditions:

1) Baseline (BASE): without visual feedback or special instructions.

2) Self-monitored (SELF): Verbal instructions to focus on spending equal amounts of time in paretic and non paretic stance.
3) Visual feedback (FB): with visual feedback about the symmetry of stance time.

4) Dual task (DT): performance of a dual task which required the participant to count backwards by 7 from a predetermined number given by the investigator.)

5.3.6 Visual Feedback Program

Visual feedback about the symmetry of stance time (FB condition) was provided on a 55” flat screen using a custom software program created in Labview 7.1 (National Instruments, Austin, TX). The program averages the stance time symmetry over 5 consecutive gait cycles (recorded with the footswitches) and displays it in real time as a white point on a Cartesian graph with symmetry on the x-axis and time in seconds on the y-axis (Figure 5.1). Stance time symmetry was calculated as the ratio of right over left stance time. An adjustable target range for symmetry was represented on the graph by two vertical yellow bars. The initial target range, 0.9 to 1.1, was based on the 95% confidence interval for healthy adults previously published\textsuperscript{169}. Participants were instructed to walk so that the symmetry plot of their gait fell within the target range. If right stance time was longer, the white symmetry plot would appear to the right of the target range and vice versa if left stance was longer. The target range was adjusted to be narrower or wider, based on the participant’s ability to maintain the symmetry of their gait within this range.

5.3.7 Data and Statistical Analysis

5.3.7.a. Temporal Gait Parameters for TM Walking

The footswitch data were analyzed using another custom software program created using Labview 7.1. Timing of footfall events was used to calculate the following temporal gait
parameters (in seconds) averaged over the entire 1 minute walking trial: stride time, swing time, stance time, left double support (DS) time (where weight is transferred from the posterior left foot to the anterior right foot), and right DS time (weight is transferred from the posterior right foot to the anterior left foot). Cadence was also calculated and reported as steps per minute. Note that throughout this paper, stance time refers to the total duration that the left or right limb is in contact with the ground (i.e. single support time and double support time combined) as opposed to single support time.

5.3.7.b. Gait Symmetry Calculations

Previous work has recommended that, for statistical purposes, gait symmetry be calculated as a ratio of right and left lower limb values with the larger value (irrespective
of paretic side) as the numerator. We have followed this convention for the symmetry calculations for over-ground gait. However, due to the real-time constraint of the visual feedback system used during TM walking and step to step variability in symmetry, symmetry calculations for TM walking, used for task comparisons, were calculated as the ratio of the paretic value divided by the non-paretic value (in seconds).

5.3.7.c. Normative Symmetry for Over-ground Gait

Normative symmetry for over-ground walking was defined using threshold values that have been described in previous work. Briefly, normative symmetry was based on the 95% confidence interval around the mean step length, swing time and stance time symmetry values of over-ground walking of 21 healthy adults. Step length symmetry values greater than 1.06, swing time symmetry values greater than 1.06 and stance time symmetry values greater than 1.08 were considered asymmetric.

5.3.7.d. EMG Analysis

EMG signal processing and data analyses were done with MyoResearch XP 1.06.04 software (Noraxon, Scottsdale, AZ). EMG signals were full-wave rectified, band pass filtered (10-250Hz, FIR) and smoothed. The EMG signals were then examined visually and any remaining artifacts were removed using the editing function in the software. EMG signals were processed relative to the gait cycle rather than to time. Each sixty second trial was fragmented into individual step cycles according to the analyzed foot switch signals and then EMG was averaged over the gait cycle.
5.3.7.e. Objective 1: Task Related Differences in Symmetry and Temporal Gait

Parameters of TM Walking

Note that analysis of the results is importantly focussed on individual differences as well as any group differences. We view the within-subject (case) analysis as particularly important in light of the heterogeneity across stroke patients. However, where possible and appropriate we have also run within group comparisons.

In order to determine the effects of verbal instruction (SELF), visual feedback (FB) and dual tasking (DT) on gait, the BASE TM walking trial was used as a baseline. Temporal gait parameters and swing and stance symmetry ratios from in the remaining 3 conditions (SELF, FB, DT) were compared to the baseline, within a participant, using unpaired t-tests. The perfect symmetry value was defined as 1.0. Gait symmetry during a TM walking condition was considered improved if it was significantly different from the BASE condition and the value had moved closer to 1.0 (compared to the symmetry recorded during the BASE condition). Finally, in order to determine if there was a common response of all participants to TM walking conditions, group comparisons were made between TM conditions. Paired t-tests were used to compare the changes in left and right stride times and cadence made during the SELF, FB and DT trials across participants.

5.3.7.f. Objective 2: Characterization of Response to Symmetry FB

As mentioned previously, the secondary objective of this study was to determine if the change in symmetry with FB was accomplished in the intended manner of increased
paretic limb use. This analysis focussed on those individuals who exhibited significantly different swing and/or stance symmetry with FB compared to the BASE condition. Two approaches were used. The first approach utilized the temporal gait parameters to determine if significant changes in the gait phases of the paretic limb contributed to the observed change in symmetry. The second approach involved visual inspection of average EMG profiles to identify differences in muscle activation. Comparison between EMG recorded for the BASE and FB conditions were performed using the Bilateral Gait Report function with the overlay option in the MyoResearch XP software. EMG signals were displayed as a mean and standard deviation (SD) band. Visual analysis of this output included three criteria: 1) determine if the EMG pattern in the BASE condition displayed normal phasic activity 2) determine if the EMG pattern in the BASE condition exhibited muscle activity at inappropriate points in the gait cycle and 3) determine if the EMG pattern in the FB condition exhibited significant changes from the BASE condition. The EMG pattern in the FB condition was considered significantly different from the BASE condition only if the SD bands broke between the two conditions.

5.4 Results

5.4.1 Participants

A total of 8 patients with stroke were included for analysis in this study. The mean (SD) age for the group was 60.6 (18.6) years and the mean time post stroke was 3.2 (1.8) months. The clinical characteristics of each participant are included in Table 5.1. Due to technical difficulties with either the feedback program and/or the footswitch equipment,
we were unable to analyze FB TM trials for 2 participants and SELF TM trials for 4 participants.

5.4.2 Over-ground Walking

Group mean and individual values for velocity, swing symmetry, stance symmetry and step length symmetry of over-ground walking are summarized in Table 5.1. Two individuals were asymmetric in step length, five individuals were asymmetric in swing time and four individuals were asymmetric in stance time.

Table 5.1 Summary of demographic data, clinical measures and spatiotemporal values for over-ground walking for each stroke participant. Symmetry ratios that fall outside the normal range, and therefore represent asymmetrical gait, are highlighted by an asterisk (*). Also included is a summary of the treadmill (TM) walking trials that were collected for each participant. Abbreviations are as follows: I=ischemic stroke, H=hemorrhagic stroke, CMSA = Chedoke McMaster Stroke Assessment, BBS = Berg Balance Scale, BASE = baseline TM trial, SELF = verbal instruction TM trial, FB =TM trial with feedback about stance symmetry and DT =TM trial with cognitive dual task.

<table>
<thead>
<tr>
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<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
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<td>78</td>
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<td>68</td>
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<tr>
<td>Gender</td>
<td>M</td>
<td>M</td>
<td>F</td>
<td>M</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>-</td>
</tr>
<tr>
<td>Time since stroke</td>
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<td>3.7</td>
<td>4.2</td>
<td>4.1</td>
<td>2.1</td>
<td>5.2</td>
<td>0.5</td>
<td>0.7</td>
<td>3.2 (1.8)</td>
</tr>
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<td>I</td>
<td>H</td>
<td>H</td>
<td>I</td>
<td>-</td>
<td>I</td>
<td>-</td>
</tr>
<tr>
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<td>L</td>
<td>R</td>
<td>L</td>
<td>R</td>
<td>R</td>
<td>L</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>4</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>5.4 (1.2)</td>
</tr>
<tr>
<td>CMSA foot (0-7)</td>
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<td>2</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>6</td>
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<td>5.5 (1.6)</td>
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<tr>
<td>BBS (0-56)</td>
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<td>51</td>
<td>52</td>
<td>56</td>
<td>42</td>
<td>48</td>
<td>50</td>
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<tr>
<td>Velocity (cm/s)</td>
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<td>140.2</td>
<td>76.1</td>
<td>117.2</td>
<td>97.9</td>
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<td>1.00</td>
<td>1.01</td>
<td>1.11*</td>
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<td>1.02</td>
<td>1.04 (0.04)</td>
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<td>Swing time symmetry</td>
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<td>1.56*</td>
<td>1.02</td>
<td>1.10*</td>
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<td>1.02</td>
<td>1.41(0.60)</td>
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<td>Stance time symmetry</td>
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<td>1.17*</td>
<td>1.01</td>
<td>1.16*</td>
<td>1.02</td>
<td>1.05</td>
<td>2.26*</td>
<td>1.01</td>
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<tr>
<td>TM speed (cm/s)</td>
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<td>49.2</td>
<td>89.4</td>
<td>26.8</td>
<td>89.4</td>
<td>62.6</td>
<td>102.8</td>
<td>84.9</td>
<td>70.96(25.22)</td>
</tr>
<tr>
<td>BASE</td>
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<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
</tr>
<tr>
<td>SELF</td>
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<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
</tr>
<tr>
<td>FB</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
</tr>
<tr>
<td>DT</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
</tr>
</tbody>
</table>
5.4.3 Treadmill Walking

All participants were able to complete all TM walking tasks successfully. Participants were able to perform TM tasks while using only 1 TM handrail for support with the exception of S6 who always required two hand support. The average self selected/preferred TM speed for the group was 70.96 (25.22) cm/s. In all but one case (S2), participants preferred a slower speed on the TM (Table 5.1) compared to their over-ground walking velocity. The swing and stance symmetry ratios for each TM walking condition are summarized, by participant, in Table 5.2.

5.4.4. Objective 1: Task Related Differences in Symmetry and Temporal Gait

Parameters of TM Walking

5.4.4. a. Task Related Differences in Gait Associated with FB

Symmetry data for the FB condition could be analyzed for 6 participants (Table 5.2). Of these 6, four participants exhibited significantly different gait symmetry compared to the BASE TM condition (S2, S3, S6, S7). In three cases (S2, S3, S6) both swing time symmetry and stance time symmetry improved (i.e. symmetry ratio moved closer to 1.0 with FB). In one case (S7) swing time symmetry and stance time symmetry was worse compared to the BASE condition.

All 6 participants, for whom data could be analyzed, exhibited significant changes in some temporal gait parameters with FB. These are included in Tables 5.3-5.5 and 5.8-5.10. In general, all but one of these 6 individuals exhibited significantly decreased stride time with FB.
Table 5.2 Swing time (swing), stance time (stance) symmetry ratios in each of the 4 TM walking conditions, for each participant. Abbreviations are as follows: BASE = baseline TM trial, SELF = verbal instruction TM trial, FB = TM trial with feedback about stance symmetry and DT = TM trial with cognitive dual task. Those symmetry values that represented a significant change from the BASE condition are indicated by an asterisk (*) (p<0.01) or cross (†) (p<0.05). Cells shaded in green indicate that the symmetry value represented an improvement (i.e. value closer to 1.0) relative to the BASE condition. Cells shaded in red indicate that the symmetry value represented a decrement (i.e. value further from 1.0) relative to the BASE condition.

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
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<th>S4</th>
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<th>S7</th>
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<tr>
<td></td>
<td>swing</td>
<td>stance</td>
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<td>stance</td>
<td>swing</td>
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<tr>
<td>BASE</td>
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<td></td>
<td>(0.04)</td>
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<td>(0.08)</td>
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<td>BASE</td>
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<td>1.02</td>
<td>1.01</td>
<td>0.99</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>(0.07)</td>
<td>(0.04)</td>
<td>(0.05)</td>
<td>(0.03)</td>
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<td>(0.02)</td>
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<td>0.99</td>
<td>0.97</td>
<td>1.03</td>
<td>0.97</td>
<td>1.02</td>
<td>0.97</td>
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<tr>
<td></td>
<td>(0.05)</td>
<td>(0.03)</td>
<td>(0.05)</td>
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<td>(0.03)</td>
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<td>(0.03)</td>
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<tr>
<td>SELF</td>
<td>-</td>
<td>-</td>
<td>0.94</td>
<td>1.04</td>
<td>-</td>
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<td>1.09</td>
<td>0.96</td>
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<tr>
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<td>(0.05)</td>
<td>(0.04)</td>
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<td>(0.06)</td>
<td>(0.03)</td>
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<tr>
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<td>0.96</td>
<td>1.04</td>
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<td>(0.02)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
</tr>
<tr>
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<td>1.05</td>
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<td>0.97</td>
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<td>0.93</td>
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<td>1.03</td>
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<tr>
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<td>(0.02)</td>
<td>(0.02)</td>
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<td>(0.02)</td>
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</table>
Table 5.3 Summary of changes in left (L) and right (R) temporal gait parameters for participant S1 who exhibited left hemiplegia. Changes that occurred with the feedback (FB) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to $p<0.05$.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>19.6</td>
<td>1.53 (0.03)</td>
<td>1.53 (0.03)</td>
<td>0.54 (0.02)</td>
<td>0.60 (0.02)</td>
<td>1.00 (0.02)</td>
<td>0.94 (0.02)</td>
<td>0.20 (0.01)</td>
<td>0.20 (0.01)</td>
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<td>FB</td>
<td>20.1</td>
<td>1.49 (0.04)</td>
<td>1.49 (0.04)</td>
<td>0.51 (0.03)</td>
<td>0.57 (0.02)</td>
<td>0.98 (0.05)</td>
<td>0.93 (0.03)</td>
<td>0.18 (0.02)</td>
<td>0.23 (0.03)</td>
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<tr>
<td>% change with FB</td>
<td>+3.0</td>
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<td>-2.8*</td>
<td>-4.5*</td>
<td>-4.6*</td>
<td>1.5</td>
<td>-1.5*</td>
<td>-8.4*</td>
<td>+13.9*</td>
</tr>
<tr>
<td>DT</td>
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<td>1.74 (0.04)</td>
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<td>1.14 (0.03)</td>
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<td>0.26 (0.01)</td>
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<tr>
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<td>+14.6*</td>
<td>+27.5*</td>
<td>+7.9*</td>
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</table>

Table 5.4 Summary of changes in left (L) and right (R) temporal gait parameters for participant S2 who exhibited right hemiplegia. Changes that occurred with the feedback (FB) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to $p<0.05$.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
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<td>1.82 (0.08)</td>
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<td>-1.0</td>
<td>-0.8</td>
<td>-20.2*</td>
<td>-0.6</td>
<td>+12.0*</td>
<td>+65.0*</td>
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<td>% change with DT</td>
<td>+1.8</td>
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<td>-1.7</td>
<td>-14.4*</td>
<td>-18.9*</td>
<td>+4.6*</td>
<td>+9.2*</td>
<td>+85.1*</td>
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Table 5.5 Summary of changes in left (L) and right (R) temporal gait parameters for participant S3 who exhibited left hemiplegia. Changes that occurred with the feedback (FB), self (SELF) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
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<td>1.32 (0.03)</td>
<td>1.32 (0.03)</td>
<td>0.51 (0.03)</td>
<td>0.48 (0.01)</td>
<td>0.81 (0.01)</td>
<td>0.84 (0.02)</td>
<td>0.15 (0.01)</td>
<td>0.17 (0.01)</td>
</tr>
<tr>
<td>FB</td>
<td>24.7</td>
<td>1.21 (0.02)</td>
<td>1.22 (0.02)</td>
<td>0.46 (0.01)</td>
<td>0.45 (0.01)</td>
<td>0.76 (0.01)</td>
<td>0.76 (0.01)</td>
<td>0.15 (0.01)</td>
<td>0.16 (0.01)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>+8.4</td>
<td>-7.8*</td>
<td>-7.8*</td>
<td>-9.9*</td>
<td>-5.9*</td>
<td>-6.4*</td>
<td>-8.8*</td>
<td>-5.2*</td>
<td>-8.9*</td>
</tr>
<tr>
<td>SELF</td>
<td>20.3</td>
<td>1.48 (0.03)</td>
<td>1.48 (0.03)</td>
<td>0.55 (0.02)</td>
<td>0.59 (0.03)</td>
<td>0.92 (0.02)</td>
<td>0.89 (0.02)</td>
<td>0.16 (0.01)</td>
<td>0.18 (0.01)</td>
</tr>
<tr>
<td>% change with SELF</td>
<td>-10.8</td>
<td>+12.0*</td>
<td>+12.1*</td>
<td>+8.6*</td>
<td>+22.0*</td>
<td>+14.2*</td>
<td>+6.2*</td>
<td>+2.5*</td>
<td>+3.0*</td>
</tr>
<tr>
<td>DT</td>
<td>22.7</td>
<td>1.32 (0.02)</td>
<td>1.32 (0.02)</td>
<td>0.52 (0.01)</td>
<td>0.49 (0.01)</td>
<td>0.81 (0.01)</td>
<td>0.83 (0.01)</td>
<td>0.15 (0.01)</td>
<td>0.17 (0.01)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>0.4</td>
<td>0.44</td>
<td>0.41</td>
<td>+2.0*</td>
<td>+2.2*</td>
<td>0.4</td>
<td>0.45</td>
<td>-2.6*</td>
<td>-5.5*</td>
</tr>
</tbody>
</table>

Table 5.6 Summary of changes in left (L) and right (R) temporal gait parameters for participant S4 who exhibited left hemiplegia. Changes that occurred with the dual task (DT) TM walking condition are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>17.1</td>
<td>1.75 (0.07)</td>
<td>1.76 (0.16)</td>
<td>0.52 (0.04)</td>
<td>0.91 (0.11)</td>
<td>1.23 (0.09)</td>
<td>0.85 (0.10)</td>
<td>0.17 (0.03)</td>
<td>0.16 (0.08)</td>
</tr>
<tr>
<td>DT</td>
<td>16.94</td>
<td>1.76 (0.11)</td>
<td>1.78 (0.16)</td>
<td>0.41 (0.04)</td>
<td>0.58 (0.19)</td>
<td>1.36 (0.08)</td>
<td>1.18 (0.15)</td>
<td>0.31 (0.08)</td>
<td>0.43 (0.14)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>1.0</td>
<td>-20.2*</td>
<td>-36.1*</td>
<td>+11.2*</td>
<td>+37.8*</td>
<td>+82.4*</td>
<td>+170.0*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.7 Summary of changes in left (L) and right (R) temporal gait parameters for participant S5 who exhibited right hemiplegia. Changes that occurred with the dual task (DT) TM walking condition are noted in reference to the baseline (BASE) TM walking condition. Cadence values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>22.0</td>
<td>1.36 (0.02)</td>
<td>1.36 (0.02)</td>
<td>0.47 (0.01)</td>
<td>0.45 (0.02)</td>
<td>0.89 (0.02)</td>
<td>0.91 (0.01)</td>
<td>0.21 (0.01)</td>
<td>0.22 (0.01)</td>
</tr>
<tr>
<td>DT</td>
<td>21.6</td>
<td>1.39 (0.02)</td>
<td>1.39 (0.02)</td>
<td>0.48 (0.01)</td>
<td>0.48 (0.01)</td>
<td>0.91 (0.02)</td>
<td>0.91 (0.01)</td>
<td>0.23 (0.01)</td>
<td>0.20 (0.01)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>1.9</td>
<td>+1.9*</td>
<td>+1.9*</td>
<td>+1.6*</td>
<td>+6.3*</td>
<td>+2.1*</td>
<td>0.12</td>
<td>+6.0*</td>
<td>-9.5*</td>
</tr>
</tbody>
</table>

Table 5.8 Summary of changes in left (L) and right (R) temporal gait parameters for participant S6 who exhibited right hemiplegia. Changes that occurred with the feedback (FB), self (SELF) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>23.6</td>
<td>1.27 (0.02)</td>
<td>1.27 (0.02)</td>
<td>0.39 (0.01)</td>
<td>0.41 (0.01)</td>
<td>0.89 (0.02)</td>
<td>0.86 (0.01)</td>
<td>0.22 (0.01)</td>
<td>0.26 (0.01)</td>
</tr>
<tr>
<td>FB</td>
<td>24.9</td>
<td>1.21 (0.03)</td>
<td>1.21 (0.02)</td>
<td>0.40 (0.02)</td>
<td>0.41 (0.01)</td>
<td>0.81 (0.02)</td>
<td>0.80 (0.02)</td>
<td>0.22 (0.01)</td>
<td>0.18 (0.01)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>5.5</td>
<td>-5.2*</td>
<td>-5.3*</td>
<td>+2.9*</td>
<td>1.22</td>
<td>-8.7*</td>
<td>-7.2*</td>
<td>+1.9*</td>
<td>-30.0*</td>
</tr>
<tr>
<td>SELF</td>
<td>23.9</td>
<td>1.26 (0.02)</td>
<td>1.26 (0.02)</td>
<td>0.39 (0.01)</td>
<td>0.43 (0.02)</td>
<td>0.86 (0.02)</td>
<td>0.83 (0.02)</td>
<td>0.24 (0.01)</td>
<td>0.20 (0.01)</td>
</tr>
<tr>
<td>% change with SELF</td>
<td>1.3</td>
<td>-1.3*</td>
<td>-1.3*</td>
<td>+1.9*</td>
<td>+4.0*</td>
<td>-2.7*</td>
<td>-3.8*</td>
<td>+9.6*</td>
<td>+23.7*</td>
</tr>
<tr>
<td>DT</td>
<td>22.7</td>
<td>1.32 (0.02)</td>
<td>1.32 (0.02)</td>
<td>0.41 (0.01)</td>
<td>0.44 (0.01)</td>
<td>0.91 (0.01)</td>
<td>0.88 (0.02)</td>
<td>0.27 (0.01)</td>
<td>0.21 (0.01)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>3.6</td>
<td>+3.7*</td>
<td>+3.7*</td>
<td>+5.4*</td>
<td>+6.3*</td>
<td>+3.0*</td>
<td>+2.5*</td>
<td>+23.1*</td>
<td>-19.5*</td>
</tr>
</tbody>
</table>
Table 5.9 Summary of changes in left (L) and right (R) temporal gait parameters for participant S7 who exhibited right hemiplegia. Changes that occurred with the feedback (FB), self (SELF) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>25.7</td>
<td>1.17 (0.01)</td>
<td>1.17 (0.01)</td>
<td>0.43 (0.01)</td>
<td>0.43 (0.01)</td>
<td>0.74 (0.01)</td>
<td>0.73 (0.01)</td>
<td>0.17 (0.01)</td>
<td>0.14 (0.01)</td>
</tr>
<tr>
<td>FB</td>
<td>27.4</td>
<td>1.09 (0.02)</td>
<td>1.09 (0.02)</td>
<td>0.41 (0.01)</td>
<td>0.40 (0.02)</td>
<td>0.68 (0.02)</td>
<td>0.69 (0.02)</td>
<td>0.14 (0.01)</td>
<td>0.14 (0.01)</td>
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<tr>
<td>% change with FB</td>
<td>6.7</td>
<td>-6.3*</td>
<td>-6.3*</td>
<td>-3.8*</td>
<td>-7.3*</td>
<td>-7.8*</td>
<td>-5.8*</td>
<td>-16.3*</td>
<td>-1.2*</td>
</tr>
<tr>
<td>SELF</td>
<td>25.4</td>
<td>1.18 (0.02)</td>
<td>1.18 (0.02)</td>
<td>0.45 (0.01)</td>
<td>0.43 (0.01)</td>
<td>0.73 (0.01)</td>
<td>0.76 (0.02)</td>
<td>0.15 (0.01)</td>
<td>0.15 (0.01)</td>
</tr>
<tr>
<td>% change with SELF</td>
<td>1.3</td>
<td>+1.3*</td>
<td>+1.3*</td>
<td>+6.3*</td>
<td>-1.1</td>
<td>-1.5*</td>
<td>+2.6*</td>
<td>-13.6*</td>
<td>+11.8*</td>
</tr>
<tr>
<td>DT</td>
<td>25.2</td>
<td>1.19 (0.01)</td>
<td>1.19 (0.01)</td>
<td>0.47 (0.01)</td>
<td>0.44 (0.01)</td>
<td>0.72 (0.01)</td>
<td>0.75 (0.01)</td>
<td>0.15 (0.01)</td>
<td>0.13 (0.01)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>1.8</td>
<td>+1.9*</td>
<td>+1.9*</td>
<td>+9.8*</td>
<td>+1.3*</td>
<td>-2.7*</td>
<td>+2.1*</td>
<td>-10.5*</td>
<td>-5.8*</td>
</tr>
</tbody>
</table>

Table 5.10 Summary of changes in left (L) and right (R) temporal gait parameters for participant S8 who exhibited left hemiplegia. Changes that occurred with the feedback (FB) and dual task (DT) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Cadence (Cad) values are in steps per minute, all other values are in seconds. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>Cad</th>
<th>L stride time</th>
<th>R stride time</th>
<th>L swing time</th>
<th>R swing time</th>
<th>L stance time</th>
<th>R stance time</th>
<th>L DS time</th>
<th>R DS time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>26.4</td>
<td>1.14 (0.02)</td>
<td>1.13 (0.02)</td>
<td>0.39 (0.01)</td>
<td>0.42 (0.01)</td>
<td>0.74 (0.01)</td>
<td>0.72 (0.01)</td>
<td>0.15 (0.01)</td>
<td>0.17 (0.01)</td>
</tr>
<tr>
<td>FB</td>
<td>29.4</td>
<td>1.02 (0.03)</td>
<td>1.02 (0.03)</td>
<td>0.35 (0.01)</td>
<td>0.37 (0.01)</td>
<td>0.67 (0.02)</td>
<td>0.65 (0.02)</td>
<td>0.14 (0.01)</td>
<td>0.16 (0.01)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>11.4</td>
<td>-10.2*</td>
<td>-10.3*</td>
<td>-10.6*</td>
<td>-10.9*</td>
<td>-10.1*</td>
<td>-10.0*</td>
<td>-10.8*</td>
<td>-7.7*</td>
</tr>
<tr>
<td>SELF</td>
<td>25.9</td>
<td>1.16 (0.02)</td>
<td>1.16 (0.04)</td>
<td>0.40 (0.01)</td>
<td>0.44 (0.04)</td>
<td>0.77 (0.04)</td>
<td>0.73 (0.01)</td>
<td>0.16 (0.01)</td>
<td>0.17 (0.01)</td>
</tr>
<tr>
<td>% change with SELF</td>
<td>2.1</td>
<td>+1.9*</td>
<td>+2.4*</td>
<td>0.2</td>
<td>+4.6*</td>
<td>+3.3*</td>
<td>+1.0*</td>
<td>+2.9*</td>
<td>1.2</td>
</tr>
<tr>
<td>DT</td>
<td>24.7</td>
<td>1.2 (0.02)</td>
<td>1.22 (0.02)</td>
<td>0.43 (0.01)</td>
<td>0.45 (0.01)</td>
<td>0.79 (0.01)</td>
<td>0.77 (0.01)</td>
<td>0.18 (0.01)</td>
<td>0.16 (0.01)</td>
</tr>
<tr>
<td>% change with DT</td>
<td>6.6</td>
<td>+7.0*</td>
<td>+7.1*</td>
<td>+7.7*</td>
<td>+7.5*</td>
<td>+6.6*</td>
<td>+6.8*</td>
<td>+17.5*</td>
<td>-5.4*</td>
</tr>
</tbody>
</table>
In addition to within individual comparisons, we also compared left and right stride times and cadence between the two TM tasks (BASE and FB), across the group. The mean change in left and right stride time with FB was 0.07 (0.04) s each. A paired t-test (n=6) revealed that this decrease in left and right stride times was statistically significant (both p<0.01).

A paired t-test (n=6) for change in cadence between BASE and FB revealed that cadence was significantly greater in the FB condition (21.7 (3.7) versus 23.9 (4.7) steps/min; p=0.019). Due to the changes in stride time between the two trials, gait parameters were also analyzed as a percentage of the gait cycle (Tables 11-16). In general, for each of the four individuals who exhibited a significant change in symmetry with FB, the percentage of cycle gait parameter that exhibited the largest change from BASE to FB was either left or right DS time.

5.4.4. b. Task Related Differences in Gait Associated with SELF

Symmetry data for the SELF condition could be analyzed for four participants (Table 5.2). Three of these four participants exhibited significantly different swing and stance symmetry in the SELF condition compared to the BASE condition (S3, S7, S8) (all p<0.01). In all three cases, swing and stance symmetry changed for the worse (i.e. ratio moved further from 1.0). The remaining participant exhibited significantly different stance symmetry only (S6) (p=0.047). In this case, stance symmetry changed for the worse compared to BASE TM walking.
All four participants, for whom data was analyzed, exhibited significant changes in some temporal gait parameters with FB (Tables 5.5 and 5.8-5.10). Overall, three individuals (S3, S7, S8) exhibited significantly higher left and right stride times in the SELF TM condition. One individual (S6) exhibited significantly lower left and right stride times in the SELF condition. These differences were not associated with differences in cadence. A paired t-test (n=4) for change in cadence between BASE and SELF across the group, revealed that cadence was not significantly different between the two conditions (21.7 (3.7) versus 23.9 (2.5) steps/min; p=0.29).

5.4.4. c. Task Related Differences in Gait Associated with DT

Symmetry data for the DT condition could be analyzed for all eight participants. Three participants exhibited significantly different symmetry in both swing time and stance time during the DT condition (S4, S5, S7) (all p<0.05). One participant exhibited significantly different stance time symmetry only (S2) (p=0.035). In three cases, symmetry improved with DT (S2, S4, and S5) and in one case (S7) symmetry was worse. Gait symmetry values during the DT TM trials for each individual are included in Table 5.2.

DT led to significant changes in temporal gait parameters in all eight participants (Tables 5.3-5.10). Five participants significantly decreased their left and right stride times with DT. The remaining three participants (S2, S3, and S4) did not significantly change their stride times. A comparison of cadence in values between BASE and DT conditions (n=8)
revealed non-significant trend towards decreased cadence in the DT condition (21.7 (3.7) versus 21.0 (3.5) steps/min; p=0.056).

5.4.5. Objective 2: Characterization of Response to Symmetry FB

The following analysis focussed on the four (of 6) participants who significantly altered their gait symmetry with FB. Temporal gait parameters are expressed as a percentage of the gait cycle.

5.4.5.a. Participant S2

The temporal gait parameters (expressed as a percentage of gait cycle) for S2 are included in Table 5.11. Participant S2 improved their stance symmetry, in response to FB, by significantly increasing the duration of affected stance (by 13%, p<0.05). It appears that this was done by prolonging the DS phase (increased by 66%, p<0.05) where weight was transferred from the unaffected to the affected limb. The change in affected stance duration was not brought about by an increase in affected single limb stance duration as the corresponding unaffected swing duration did not change. This participant improved their swing symmetry with FB by decreasing the duration of affected swing (by 19%, p<0.05).

Table 5.11 Summary of changes in percentage of left (L) and right (R) gait cycle parameters for participant S2 who exhibited right hemiplegia. Changes that occurred with the feedback (FB) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>% L swing</th>
<th>% R swing</th>
<th>% L stance</th>
<th>% R stance</th>
<th>% L DS</th>
<th>% R DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>33.39 (1.50)</td>
<td>39.93 (2.31)</td>
<td>66.67 (1.61)</td>
<td>60.08 (2.54)</td>
<td>12.31 (0.95)</td>
<td>14.40 (1.49)</td>
</tr>
<tr>
<td>FB</td>
<td>33.30 (1.49)</td>
<td>32.17 (1.10)</td>
<td>66.63 (1.99)</td>
<td>67.95 (1.71)</td>
<td>20.43 (1.12)</td>
<td>14.04 (0.95)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>0.29</td>
<td>-19.43*</td>
<td>0.06</td>
<td>+13.10*</td>
<td>+65.90*</td>
<td>2.47</td>
</tr>
</tbody>
</table>
EMG profiles of BASE (green) and FB (red) TM conditions are included in Figure 5.2. During the BASE condition the paretic (right) limb exhibited co-contraction of all four muscles during early to mid stance (0-30%). The non-paretic (left) limb exhibits the expected phasic activity in all four muscles. The FB condition exhibits a significant difference in activity of the paretic limb medial.

**Figure 5.2** EMG gait profile for participant S2 during the BASE (green) and FB (red) TM walking conditions. EMG was recorded from the non-paretic limb tibialis anterior (a), medial gastrocnemius (b), semitendinosus (c) and vastus lateralis (d). EMG was also recorded from the paretic limb tibialis anterior (e), medial gastrocnemius (f), semitendinosus (g) and vastus lateralis (h). The vertical green and red lines denote the transition from stance to swing in the BASE and FB conditions respectively. Significant changes in muscle activity are highlighted with arrows.
gastrocnemius between 60% and 70% of the gait cycle. This appears to be attributable to a phase shift related to changes in the duration of the paretic stance phase.

5.4.5.b. Participant S3

The temporal gait parameters (expressed as a percentage of gait cycle) for S3 are included in Table 5.12. Participant S3 also changed their gait symmetry in the desired manner using a slightly different approach. Stance symmetry was improved by significantly increasing both the duration of affected stance (1.5%, p=0.05) and decreasing the duration of unaffected stance (1.1%, p=0.05) so that the values became more equal (i.e. more symmetrical). In contrast to S2, S3 increased the affected stance duration by increasing both affected single limb support (evidenced by the increase in corresponding unaffected swing duration) (2%, p=0.05) and prolonging the shift of weight from the affected to the unaffected limb during the DS phase (2.8%, p=0.05). Paralleling the changes in stance symmetry, S3 improved their swing symmetry by decreasing affected swing (2.2%, p=0.05) and increasing unaffected swing duration (25, p=0.05) so that the values were more equal.

<table>
<thead>
<tr>
<th>BASE</th>
<th>% L swing</th>
<th>% R swing</th>
<th>% L stance</th>
<th>% R stance</th>
<th>% L DS</th>
<th>% R DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>38.47 (1.91)</td>
<td>36.42 (0.69)</td>
<td>61.46 (0.93)</td>
<td>63.50 (1.85)</td>
<td>11.74 (0.61)</td>
<td>13.27 (0.70)</td>
</tr>
<tr>
<td>FB</td>
<td>37.61 (0.97)</td>
<td>37.15 (0.83)</td>
<td>62.37 (1.18)</td>
<td>62.78 (1.15)</td>
<td>12.07 (0.61)</td>
<td>13.11 (0.74)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>-2.2*</td>
<td>+2.0*</td>
<td>+1.5*</td>
<td>-1.1*</td>
<td>+2.8*</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 5.12 Summary of changes in percentage of left (L) and right (R) gait cycle parameters for participant S3 who exhibited left hemiplegia. Changes that occurred with the feedback (FB) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.
EMG profiles of BASE (green) and FB (red) TM conditions are included in Figure 5.3. During the BASE condition the paretic (left) limb exhibited phasic activity of all four muscles throughout the gait cycle. The non-paretic (left) limb also exhibits the expected phasic activity in all four muscles. There is a significant increase in the activity of the paretic limb semitendinosus with FB at 30% of the gait cycle. There is also a significant increase in the activity of the non-paretic limb semitendinosus at 90% of the gait cycle.

Figure 5.3 EMG gait profile for participant S3 during the BASE (green) and FB (red) TM walking conditions. EMG was recorded from the paretic limb tibialis anterior (a), medial gastrocnemius (b), semitendinosus (c) and vastus lateralis (d). EMG was also recorded from the non-parietic limb tibialis anterior (e), medial gastrocnemius (f), semitendinosus (g) and vastus lateralis (h). The vertical green and red lines denote the transition from stance to swing in the BASE and FB conditions respectively. Significant changes in muscle activity are highlighted with arrows.
5.4.5.c. Participant S6

The temporal gait parameters (expressed as a percentage of gait cycle) for S6 are included in Table 5.13. Participant S6 improved stance symmetry by significantly decreasing both stance durations (both p<0.05), unaffected (3.8%) more than affected (2.1%), resulting in more equal values (i.e. improved symmetry). Similarly, improvement in swing symmetry was achieved by the same strategy: both swing phases were significantly increased (both p<0.05) and unaffected increased (8.5%) more than unaffected (4.3%).

Table 5.13 Summary of changes in percentage of left (L) and right (R) gait cycle parameters for participant S6 who exhibited right hemiplegia. Changes that occurred with the feedback (FB) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>% L swing</th>
<th>% R swing</th>
<th>% L stance</th>
<th>% R stance</th>
<th>% L DS</th>
<th>% R DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>30.24 (1.17)</td>
<td>32.25 (0.88)</td>
<td>69.78 (1.55)</td>
<td>67.76 (0.99)</td>
<td>17.21 (0.49)</td>
<td>20.32 (0.96)</td>
</tr>
<tr>
<td>FB</td>
<td>32.81 (1.40)</td>
<td>33.62 (1.14)</td>
<td>67.16 (1.61)</td>
<td>66.34 (1.37)</td>
<td>18.49 (0.74)</td>
<td>15.02 (0.74)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>+8.5*</td>
<td>+4.3*</td>
<td>-3.8*</td>
<td>-2.1*</td>
<td>+7.4*</td>
<td>-26.1*</td>
</tr>
</tbody>
</table>

EMG profiles of BASE (green) and FB (red) TM conditions are included in Figure 5.4. During the BASE condition, the paretic limb semitendinosus exhibited relatively minimal activity compared to the other muscles and the normal phasic activity is absent. The remaining paretic limb muscles and the non-paretic limb muscles exhibit the expected phasic activity. In the FB condition there is a significant increase in the activity of the paretic limb semitendinosus between 10% and 40% of the gait cycle. There is a significant decrease in activity of the non-paretic limb medial gastrocnemius between
15% and 20% of the gait cycle and a significant increase in the activity of the non-paretic limb semitendinosus between 5% and 10% of the gait cycle.

5.4.5.d. Participant S7

In contrast the previous 3 individuals cases, participant S7 exhibited worse swing and stance asymmetry with FB and this was due to a significant decrease in unaffected stance.
duration (1.6%) and an increase in unaffected swing duration (2.6%) respectively (both p<0.05) (Table 5.14).

Table 5.14 Summary of changes in percentage of left (L) and right (R) gait cycle parameters for participant S7 who exhibited right hemiplegia. Changes that occurred with the feedback (FB) TM walking conditions are noted in reference to the baseline (BASE) TM walking condition. Parameters that exhibited a significant difference from the BASE condition are indicated by an asterisk (*) next to the percentage change exhibited by that parameter. Significance was set to p<0.05.

<table>
<thead>
<tr>
<th></th>
<th>% L swing</th>
<th>% R swing</th>
<th>% L stance</th>
<th>% R stance</th>
<th>% L DS</th>
<th>% R DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>36.56 (0.90)</td>
<td>36.87 (0.64)</td>
<td>63.44 (0.79)</td>
<td>63.14 (0.82)</td>
<td>14.80 (0.52)</td>
<td>11.77 (0.72)</td>
</tr>
<tr>
<td>FB</td>
<td>37.52 (0.89)</td>
<td>36.47 (1.37)</td>
<td>62.41 (1.44)</td>
<td>63.48 (1.40)</td>
<td>13.22 (0.65)</td>
<td>12.71 (0.96)</td>
</tr>
<tr>
<td>% change with FB</td>
<td>+2.6*</td>
<td>1.1</td>
<td>-1.6*</td>
<td>0.5</td>
<td>-10.7*</td>
<td>+8.0*</td>
</tr>
</tbody>
</table>

EMG profiles of BASE (green) and FB (red) TM conditions are included in Figure 5.5.

During the BASE condition, there is relatively minimal activity in the paretic limb medial gastrocnemius and the expected phasic activity is absent. The phasic activity of the non-paretic limb semitendinosus is also absent. In the FB condition there is a significant increase in activity in the paretic limb medial gastrocnemius (20% to 35% of cycle) and semitendinosus (5% to 25% of cycle). There was a significant decrease in the activity of the paretic limb vastus lateralis between 5% and 15% of the gait cycle. On the non-paretic side, the semitendinosus exhibited a significant increase in activity between 0% and 10% of the gait cycle with FB. The non-paretic limb vastus lateralis exhibited a significant decrease in activity between 60% and 90% of the gait cycle.
The main finding of this study is that some individuals with stroke are capable of significantly altering their temporal gait symmetry with visual feedback during treadmill walking. However, individuals differed in their preferred strategy to respond to the FB
and they did not necessarily produce improved gait symmetry in the intended manner: through increased use of the paretic lower extremity.

Four of six participants exhibited significantly different gait symmetry in response to FB. Importantly, all six participants exhibited significantly different temporal gait parameters in response to FB indicating they all attempted to respond to the FB and some were more successful than others. Group comparisons between the BASE and FB TM conditions revealed significantly decreased left and right stride times and significantly increased cadence. This reveals that participants took shorter, faster steps with FB. Although step length was not measured, shorter steps can be assumed given the treadmill speed was held constant. This strategy of shortening steps may have been used to make walking more stable thereby enabling participants to make changes to stance and swing durations of the affected limb in response to FB. The other common feature among all participants was that DS time was the temporal gait parameter that exhibited the greatest change with FB. Again, this may reflect the strategy of altering the temporal gait pattern during the most stable phase of gait.

Apart from the commonalities listed above, it appears that the four participants who significantly altered their gait symmetry with FB, each adopted a unique strategy for doing so. The intention of the visual FB was to encourage use of the paretic LE. The objective was to have participants improve their temporal gait symmetry by altering the duration of gait phases of the paretic LE. Of the four participants who significantly altered their gait symmetry, only two did so in the desired manner. Paralleling the
observed inter-individual variation in changes in temporal parameters, changes in EMG profiles associated with FB varied among these four participants. In general, FB did not evoke improved phasic activity in any of lower extremity muscles recorded, in any participant, with one exception. Participant S6 exhibited increased paretic limb semitendinosus activity during an appropriate phase of the gait cycle (i.e. 0-35%\textsuperscript{170}). Overall, EMG did not exhibit as many changes as would be expected when phases of the gait cycle are significantly changed. Although FB was not associated with improved phasic muscle activity, it could perhaps be considered a positive outcome that FB was not associated with a worsening of the EMG profile as might be characterized by increased co-contraction of antagonist muscle pairs, out-of-phase contractions and/or premature muscle activity with respect to the gait cycle (i.e. spasticity).

Variation in strategies employed by individuals in response to an encouraged use intervention has been previously reported\textsuperscript{125}. In the current study, some participants adopted the unintended approach of altering the temporal parameters of their unaffected side in order to achieve improved symmetry in response to FB. Our finding of altered motor control of the unaffected leg in response to intervention, corresponds to the results of an EMG feedback paradigm reported by Sibley and coauthors\textsuperscript{125}. In this study, investigators found that stroke individuals could decrease the activation of unaffected vastus lateralis (VL), but not increase activation of affected VL, in response to EMG FB given during an aerobic cycle ergometry task\textsuperscript{125}. The authors suggest improved performance might be induced by modification of the program to provide FB more frequently\textsuperscript{125}. Although, in the current study, FB was provided frequently (FB displayed
on every 5th gait cycle), modification of the intervention might produce greater changes in the paretic limb. In this case, a more specific FB paradigm might have been of greater benefit. For example, the program could be modified so that symmetry is calculated in the background, and based on this calculation; a target specific to the affected single limb support (or swing) duration could be displayed for the individual. Therefore, the FB program would encourage changes specific to the paretic LE.

Our results demonstrate another important issue for gait interventions: the need for immediate monitoring of the ongoing effects or changes to the gait pattern associated with the intervention. In the current study, not all patients altered their gait symmetry in the intended way. Visual observation alone does not allow the investigator (or therapist) to detect subtle changes to the temporal gait pattern. Therefore, the unintended consequences of the FB program were not detected until after the data collection session, during data analysis. On-line monitoring of temporal (and spatial) gait parameters would enable the investigator/therapist to provide corrections to the stroke patient immediately and encourage a strategy of increased paretic limb use in response to symmetry FB. Presumably this would increase the effectiveness of the intervention.

Despite some unintended consequences, the current results suggest that FB is more effective at inducing a change in temporal gait symmetry than simple verbal instructions to walk more symmetrically. In fact, verbal instructions seemed to induce a worsening of gait symmetry. There are several possible explanations for this result. The first explanation is simply communication error. The verbal instructions provided may not
have clearly conveyed the desired gait change or goal to the participants. A second explanation may be that participants understood the instructions but knowledge of performance during the TM trial was not available. As noted above, subtle changes in the timing of gait phases are not apparent to the naked eye and so the investigators would not be able to provide additional verbal instructions to correct errors in participant performance. A third explanation is sensory and/or perceptual deficits. Participants might have been unable to perceive, process or utilize sensory information from their LEs to monitor their own performance and determine if they were in fact walking more symmetrically. It is possible that visual FB can avoid some of these complications with verbal instruction, through the knowledge of results and immediacy of the FB, resulting in a more effective method to train gait symmetry.

In contrast to the FB and SELF conditions, DT had a more varied effect on gait symmetry. Variation in response to DT within a group of individuals post-stroke has been previously reported. Regardless of the individual variation, decrement in gait performance with DT is generally believed to reflect cognitive-motor interference. Despite the variation in gait symmetry with DT, a general trend in temporal gait parameters was apparent: five (of 8) participants exhibited increased stride time and there was a non-significant trend for decreased cadence, consistent with previous DT literature. This suggests that the secondary cognitive task did cause cognitive-motor interference resulting in a decrement in some measures of gait performance. More importantly, the pattern of changes in temporal gait parameters and
symmetry is unique from that exhibited in the FB condition, suggesting that our FB results are not simply attributable to dual tasking effects.

There is one exception that should be discussed further: the participant that exhibited worse asymmetry with FB (S7). Interestingly this individual also exhibited the greatest number of changes in EMG, none of which can be interpreted as an improvement. This individual exhibited the greatest degree of swing (2.79) and stance (2.26) asymmetry in their over-ground gait suggesting that their control of gait was the most impaired. In contrast, this individual exhibited the second fastest preferred over-ground velocity (117.2 cm/s) and was capable of walking the fastest on the TM (102.8 cm/s) indicating that their capacity for gait is much less impaired. During the BASE TM condition this individual exhibited perfect stance symmetry (1.0) and near perfect swing symmetry (1.01). The interpretation of these findings is not immediately clear but it is quite likely that the absence of more meaningful disruption to symmetry during TM walking limited the ability to detect any positive change. Alternatively the decrement in symmetry with FB may be attributed to the effect of dual-tasking. As noted this effect has been previously observed. It is possible that FB may have produced cognitive-motor interference through dual-tasking effects in this one individual. This is supported by the observation that this individual was also the only person to exhibit worse asymmetry in the DT TM condition. Therefore, instead of inducing more symmetrical gait, the cognitive effort required to analyze and respond to the FB may have resulted in a decrement in the control of gait leading to greater asymmetry compared to the BASE condition.
In conclusion, it appears that some stroke patients are capable of improving their temporal gait symmetry in response to FB during TM walking. This suggests that gait asymmetry is responsive to interventions that specifically target this gait parameter. However, it appears that individuals with stroke employ different strategies to achieve improved gait symmetry and this does not always involve increased paretic limb use as was intended. This issue may be solved by on-line monitoring of gait parameters during the intervention and modifications to the FB program to provide a training target specific to the paretic limb and the patients’ specific capabilities. Future work should investigate the effectiveness of paretic-limb specific FB training and the carryover of symmetry training to over-ground gait.
6.0 Discussion

6.1 Overview of findings

This thesis has contributed new evidence regarding the asymmetrical nature of post-stroke gait and has made recommendations regarding the most appropriate way to calculate and express gait asymmetry. The specific findings of each study are summarized in Table 6.1.

Post-stroke gait asymmetry is a feature that has been measured and documented since the early 1980s. However, this feature of post-stroke gait has received considerably less attention than another feature: slow walking speed. Various gait symmetry calculations have been devised and numerous gait parameters have been analyzed for symmetry. Although symmetry equations are highly correlated, similar in data distribution and similar in discriminative ability, the simple ratio holds the advantage of ease of interpretation. Therefore the symmetry ratio is recommended for use on the basis of clinical usefulness (Study 1). There is a distinction between spatial gait asymmetry and temporal gait asymmetry in terms of their inter-relationships and their unique relationships with velocity (Study 1). Furthermore, they appear to behave differently across the various stages post-stroke. Temporal asymmetry as measured by the swing time ratio and the stance time ratio, appears to be worse in the later stages post-stroke whereas the trend for differences in spatial asymmetry across the various stages post-stroke- is less clear (Study 2). Finally, although there is a close relationship between swing time symmetry and stance time symmetry, they likely reflect different aspects of
<table>
<thead>
<tr>
<th>Study</th>
<th>Primary objective(s)</th>
<th>Major finding(s)</th>
<th>Interpretation</th>
</tr>
</thead>
</table>
| 1. Evaluation of gait symmetry after stroke: a comparison of current methods and recommendations for standardization | a. to determine if the measures provided unique information about characteristics of gait symmetry in a group of community-dwelling, ambulatory individuals with stroke  
   b. to make a recommendation regarding the most suitable candidate for standardization | symmetry equations were highly correlated and similar in both data distribution and discriminative ability  
   temporal parameters with exception of DS time were highly correlated  
   spatial parameter had a weaker correlations to velocity and temporal symmetry  
   swing and stance time symmetry differed in their discrimination of asymmetric and symmetric individuals | No equation has a unique advantage therefore symmetry ratio recommended on basis of clinical usefulness as it is easily interpreted  
   Swing time, stance time and step length symmetry ratios should be calculated to give a complete picture of an individual’s control of gait |
| 2. Changes in gait symmetry and velocity after stroke: a cross sectional study from weeks to years after stroke | to investigate the potential for significant deterioration in gait over the long term post stroke | Swing and stance time symmetry demonstrated a significant increasing linear trend across the stages post-stroke  
   Velocity, neurologic deficit and motor impairment did not demonstrate this linear trend. | There may be a decline in the control of gait (symmetry) in the later stages post-stroke  
   The capacity for gait (velocity) appears to remain constant across the stages post-stroke |
| 3. Feasibility of a rehabilitation intervention to influence gait symmetry in subacute ambulatory stroke patients | a. to determine if subacute stroke patients could significantly alter their gait symmetry in response to biofeedback.  
   b. to determine if the change in symmetry was accomplished in the intended manner of increased paretic limb use | Some individuals significantly improved their gait symmetry in response to visual feedback  
   Individuals varied in terms of the strategy employed to walk more symmetrically | Some individuals post-stroke are capable of generating a more symmetrical gait pattern in response to visual feedback  
   Feedback about gait symmetry does not necessarily encourage increased use of the paretic limb during TM walking |
gait control (Study 1). Measurement of all three symmetry ratios (step, swing and stance) will provide a detailed picture of the control of gait in an individual post-stroke.

Given that asymmetry is associated with potential negative consequences (e.g. challenges to balance control, risk of musculoskeletal injury to the non-paretic LE, loss of BMD in the paretic LE and gait inefficiency) and that it may worsen in the later stages post-stroke, it is an important issue to address in rehabilitation. This thesis has demonstrated that some stroke patients can alter their gait pattern in response to visual feedback in order to improve symmetry during TM walking (Study 3). These results demonstrate that the stroke patient not only has the ability to improve their capacity for walking (i.e. increase velocity or distance walked) but also to improve their control of walking.

6.2 Measurement of post-stroke gait

There is a consensus among researchers and clinicians about the importance of objective measurement. However, the best approach to the measurement of post-stroke gait is a matter of ongoing debate. Suggestions about appropriate or ideal measures in the literature are commonly restricted to a single index of gait function. For example, many people have commented on the suitability of velocity\textsuperscript{40,87}, the 6MWT\textsuperscript{79} and clinical scales such as the RMI\textsuperscript{78} and the FAC\textsuperscript{173}. This thesis has advocated for the use of symmetry ratios as measures of gait control, in addition to measures such as velocity, as a means of characterizing post-stroke gait. However, all of these individual measures, when used in isolation, are unlikely to provide all the pertinent information required for the study and rehabilitation of post-stroke gait. It is necessary to view the measurement of post-stroke gait in a broader context in order to form a unified, comprehensive approach.
A general principle is that the approach to gait measurement should be guided by the approach to intervention. Historically the philosophy behind post-stroke rehabilitation was one of increasing function by increasing the effectiveness of a compensatory strategy. While this is a valid approach, current neurorehabilitation theory, based on the principles of neuroplasticity, advocates for the improvement of function through the restitution of neurological deficits\textsuperscript{86}. Therefore, there is a need for clinically useful measures of neurological deficits if this is the level at which rehabilitation interventions are aimed. It has also been suggested that indices of function are important to use in rehabilitation since these evaluate outcomes that are of importance to the patient (i.e. at the level of activity and participation)\textsuperscript{174}. The rationale for the use of functional measures is supported by the fact that traditional measures of impairment do not relate strongly to activity or participation outcomes\textsuperscript{174}. But as Wade and coauthors state, successful performance on functional measures “includes a large element of adaptation by the patient to his disability and this does not necessarily reflect neuronal recovery”\textsuperscript{133}. For example, an individual may achieve an adequate score on a functional outcome measure (e.g. RMI) that reflects independence, or achieve an adequate gait velocity, but can still exhibit poor control of their gait (i.e. temporal asymmetry) due to persisting underlying neurological deficits. While this debate of functional measure versus impairment measure is relevant to the evaluation of post-stroke gait, it is possible that there exists another level between impairments and gait function. This intermediate level will be referred to as gait-specific impairment (or more simply gait impairment) and it is the position of this
thesis that this level is also important to measure for both the evaluation and rehabilitation of post-stroke gait.

Measures of gait function are important and can be used both as a means of measuring an individual’s capacity for walking as well as measuring rehabilitation outcomes (i.e. to evaluate the effectiveness of an intervention)\textsuperscript{174}. Measures that can be classified as indices of gait function include (e.g. BI, RMI, MAS), gait velocity, the 6MWT and the TUG. Traditional measures of body impairment, such as the CMSA, the Ashworth scale and muscle strength tests (e.g. manual muscle testing or isokinetic dynamometry), are also important as they give a sense of the extent of impairment resulting from stroke. However, as stated above, these measures do not necessarily strongly relate to an individual’s gait performance. They may however, relate more closely with the proposed intermediate level of gait-impairments. The term gait-impairment is related to the ICF definition of impairment and for the purposes of this discussion, relates to significant deviations that may only be apparent during gait and not immediately obvious when an individual is at rest or in a quiet state. Gait-impairments have a direct influence on an individual’s gait function or capacity for gait and are likely related to and/or influenced by impairments (e.g. weakness, sensory loss). One example is spasticity. Spasticity is a common impairment post-stroke that is traditionally measured at rest with a clinical scale such as the Ashworth\textsuperscript{175}. The trait measured by the Ashworth scale: resistance to passive muscle stretch, would be classified as an impairment\textsuperscript{68}. Lamontagne and coauthors\textsuperscript{68} note that “the expression of spasticity in the resting muscle differs from that observed under dynamic conditions” and hence they developed a locomotor-specific measure of spasticity during gait. This trait, spasticity during gait, is an example of gait impairment.
Interestingly, the locomotor-specific measure of spasticity is more strongly related to a measure of gait capacity/function (velocity, $r=-0.47$) than to traditional impairment measures including the FM, ($r = -0.28$) and measures of dorsiflexor and plantarflexor strength ($r=-0.19$ and $r=-0.12$ respectively)$^{68}$. The impact of spasticity on gait performance cannot be evaluated when the individual is at rest. Its influence becomes apparent only when an individual is walking. This locomotor-specific measure of spasticity as a gait impairment provides insight to how it affects walking performance and could guide rehabilitation interventions aimed at improving gait function through restitution of this deficit.

Another example of gait impairment is symmetry (temporal and spatial). Asymmetry becomes apparent only when an individual is walking and, as discussed in this thesis, is not necessarily predicted from measures of limb-specific impairment. It provides a measure of the parallels between the two LEs so that inter-limb ratios of step length, swing time and stance time provide some insight to the underlying control of gait$^{96,145}$. Temporal and spatial symmetry measures are more complex than a locomotor-specific measure of spasticity since it likely represents the influences and interactions of multiple impairments. For example, asymmetry in swing time such that paretic swing is longer than non-paretic swing, may be due to any one or combination of the following factors 1) insufficient power generation by the plantarflexors at push off, 2) insufficient power generation by the hip flexors at initial swing and/or 3) lack of coordination or control of preparation for foot placement at terminal swing. Each of these issues can be linked to an impairment traditionally measured at rest: muscle strength of hip flexors and
plantarflexors and coordination of the LE. However, it is unlikely that these measures, traditionally taken at rest, would indicate the level of an individual’s gait performance or the quality of gait control. A measure of symmetry on the other hand, is able to reflect the impact of these impairments on the control of gait.

One limitation of the current approach to symmetry measurement is the reliance on spatiotemporal variables. Alternatives include kinematic and kinetic variables, although these are rarely examined in individuals with stroke\textsuperscript{37}. Kinetic variables may be informative since they provide insight into the cause of movement\textsuperscript{37}. Kinematic variables may have increased discriminative ability since individuals with similar gait velocity and symmetry ratios may have differing kinematic profiles. The usefulness of these variables as symmetry ratios needs to be investigated further as they are likely to provide additional insight into the control of gait. However, the current focus on spatiotemporal parameters is appropriate since these are most likely to be adopted in the clinical setting in the short-term due to their ease of implementation and relative low cost as compared to kinematic and kinetic measurement. Additionally, Kim and Eng\textsuperscript{37} found that symmetry in GRF was correlated with temporal symmetry measures. Balasubramanian and coauthors\textsuperscript{56} demonstrated that step length asymmetry is associated with propulsive force generation by the paretic LE. These findings highlight the potential for spatial and temporal asymmetry ratios to be used as a clinical proxy measures for kinetic profiles in post-stroke gait.
To summarize, a comprehensive approach to post-stroke gait measurement must include measures of both gait function and gait impairments. The gait impairment measures can be used to understand the factors contributing to an individual’s gait dysfunction as well as guide clinical decision making regarding treatment targets and choice of intervention. Measures of gait function can be used to describe an individual’s overall gait performance, indicate how gait might impact participation and serve as an outcome measure to document the effectiveness of an intervention.

### 6.3 Treatment of post-stroke gait

As stated previously, the current approach to post-stroke rehabilitation is guided by the principles of neuroplasticity. One relevant principle is that practice induces plastic dynamic changes in the central nervous system (CNS). Fisher and Sullivan note that rehabilitation aimed at taking advantage of plasticity in the CNS should emphasize recovery versus compensation by including practice of movement patterns that incorporate the affected extremities. Although repetition of a movement pattern is important, it seems that it cannot drive plastic changes alone. Fisher and Sullivan describe four other specific practice variables that are key to effectively inducing plastic changes in the CNS based on the experimental animal literature. The first variable is task complexity. Physical activity paired with cognitive stimulation (complex task) appears to induce structural changes in the brain not associated with simple motor activity alone. The second variable is task difficulty associated with learning a new motor skill. The process of motor skill acquisition drives CNS plasticity and not simple repetitive motor activity. Specificity is the third important task variable. Practice of a specific task not only results in improved performance of that task, but also drives plastic changes within
specific cortical representations of the associated muscle actions for that task. The fourth task variable important for plasticity is sensory experience. The sensory consequences of task practice are as important for promoting neurological recovery as the process of motor skill acquisition.

The novel intervention for gait asymmetry presented in paper 3 of this thesis follows the recommendations outlined by Fisher and Sullivan and therefore, if used as a training paradigm over a longer period, may encourage recovery through influence neuroplastic changes in the brain, instead of recovery through compensation. In addition, the FB intervention addresses at least three of the four key task variables. Adjusting the gait pattern in response to real-time visual FB involves both repetition of a motor sequence as well as cognitive stimulation and it is therefore a complex task. In addition, this process involves acquisition of new motor skill which increases the difficulty of the task. Finally, the intervention is obviously task specific: it is designed to train the exact desired outcome, symmetrical gait. However, it should be reinforced that the characteristics of the FB may need to be tailored to the unique abilities of the patient to achieve optimal results.

The second paper of this thesis suggested that the control of gait may decline in the later stages post-stroke, once the period of active rehabilitation is complete. It is possible that current rehabilitation approaches to post-stroke gait do not effectively induce recovery related to plastic changes in the CNS. Current clinical practice that includes both over-ground and TM gait training may not encourage use of the paretic limb to a degree
sufficient to induce plastic changes. Instead, current approaches may only result in improving the efficiency of compensatory behaviours so that gait function improves but the underlying gait impairments do not change. For example, Buurke and colleagues\textsuperscript{134} demonstrated that improvements in gait function measures (FAC and RMI), gained with inpatient rehabilitation, can occur without significant changes in the timing of muscle activation in paretic leg (as measured by EMG). This demonstrates that functional gait improvement is related to compensatory, adaptive mechanisms rather than recovery of neurological deficits such as inappropriate sequencing of muscle activity\textsuperscript{134}. The authors suggest that these results favour “the use of adaptive, compensatory movement strategies and the encouragement of synergy-dependent motor control to improve gait” as opposed to approaches aimed at restoring deficits\textsuperscript{134}. However, these results do not imply that if rehabilitation interventions could induce neurological recovery through plastic CNS changes that gait function would not improve. An alternative interpretation, and the position of this thesis, is that current rehabilitation approaches are simply not complex, difficult or specific enough to induce plastic changes that would lead to recovery of neurological deficits and hence result in improved gait function.

It is possible that the decline in gait control, as suggested by the second paper of this thesis, is related to the fact that current rehabilitation approaches encourage the refinement of compensatory behaviour to improve function. New gait rehabilitation approaches that encourage the use of the paretic LE and thereby induce plastic changes may prevent this decline in gait control. The patient would be discharged from rehabilitation with adequate gait function that resulted from addressing the contributing
gait impairments. Therefore, the effort of hemiparetic gait would be normalized, the
negative consequences of asymmetric gait would be avoided and the patient would not be
inclined to reduce their overall walking activity. Hence, the ensuing decline in gait
control would be avoided.

6.4 Future Directions

The results of the current work present a number of directions for future studies. One
important direction is the determinants of spatial and temporal asymmetry. There has
been some speculation. For example, stance asymmetry might be due to the inability to
control the body’s centre of mass as it moves anterior over the paretic LE. This postural
instability may lead an individual to shorten the single limb support phase of the paretic
LE leading to the observed asymmetry\textsuperscript{53}. This is a plausible explanation that needs to be
established empirically. Identifying these contributing factors will facilitate use of
symmetry measures as indices of gait impairment.

Another important area of focus is development of a comprehensive approach to post-
stroke gait measurement. A three-level model which includes impairment, gait
impairment and gait function may serve both rehabilitation research and clinical practice.
Much more work is needed to indentify other gait impairments and to establish their links
to both body impairment and gait function.

One final area of focus is investigating rehabilitation interventions that aim to ameliorate
gait impairments. Further development and improvement of a symmetry FB program that
specifically encourages paretic limb use and is tailored to a patient’s abilities is needed. An important direction would be to determine if training symmetrical gait on the TM leads to more symmetrical gait over-ground. In addition, it would be valuable to determine if such an intervention, designed to encourage paretic LE use, leads to plastic changes in the brain as measured by neuroimaging techniques such as fMRI or near infrared spectroscopy. It is important to identify the interventions that induce adaptive neuroplastic changes and establish the optimal dose and timing of these types of interventions within the post-stroke recovery period. This will lead to gait rehabilitation programs that induce recovery of neurological deficits versus compensatory behaviours which can ultimately result in lasting improvement in gait function.
7.0 References


