Getting Up To Speed: Understanding The Factors Associated With Post-Stroke Gait Velocity

by

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Abstract

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The factors that influence gait velocity post-stroke are not clearly understood. This thesis sought to uncover the factors associated with gait velocity, particularly those related to maximum velocity. The first of two studies investigated the associations between physical factors and preferred and maximum gait velocity. Analysis revealed that individuals with stroke were able to increase gait velocity from preferred and that this increase, along with the achieved velocity, were related to functional balance. The second study characterized the strategy individuals used to increase gait velocity, and compared between the stroke and healthy population. It also probed the relationships between cadence, step length, strategy, and post-stroke impairment. This study demonstrated that individuals with stroke rely more on cadence than step length to increase gait velocity. These results revealed the role of balance control on limiting gait velocity and the need for specific measures of impairment in research to direct clinical practice.
Acknowledgements

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List of Abbreviations

BBS – Berg Balance Scale

CMSA – Chedoke-McMaster Stroke Assessment

MAS – Modified Ashworth Scale

ROM – Range of Motion

SD - Standard Deviation
1.0 Introduction

Stroke is a leading cause of disability within Canada (Statistics Canada, 2011). Every year, more individuals are living with the effects of stroke, leading to an increased need for rehabilitative and long-term care services. Depending on the severity and location of the stroke, individuals can be left with any number of debilitating impairments (Nyberg & Gustafson, 1996), ranging from motor dysfunction and abnormal tone to sensory and perceptual deficits (Duncan, 1994). These impairments pose difficulties for individuals when trying to regain their level of pre-stroke independence.

Of the limitations that can result from stroke, mobility impairment reported to be the most debilitating; its resolution is an important outcome for rehabilitation (Bohannon et al., 1988). With two out of three individuals being left with some level of gait impairment (Jorgensen et al., 1995), research focused on this specific limitation is paramount. Gait impairment can be characterized by temporal and spatial asymmetries, as well as a slowed gait velocity. While investigation and quantification of asymmetry within this population is important to uncover various compensatory mechanisms during gait, improvements in symmetry fail to provide similar improvements in velocity or independence (Teixeira-Salmela et al., 2001). Gait velocity however, is a consistent focus of rehabilitation and is a strong predictor of walking within the community following stroke (van de Port et al., 2008). Residual mobility deficits, including challenges with the regulation and maximization of gait velocity, can lead to difficulties with activities of daily living and community walking once discharged from acute care or rehabilitation.
For healthy individuals, gait velocity is related to lower limb muscular strength, anthropometrics and age (Bohannon, 1997). Once an individual experiences a stroke, there is an increase in the complexity of the relationship between physical function and gait velocity, specifically maximum gait velocity. Much research has looked at the impairments affecting maximum velocity following stroke, yet little consistency has been found between studies. While there are potentially many factors that could influence maximum gait velocity (Figure 1), the current study will focus on a select few composite measures which have been shown to encompass many of the most important factors noted in previous research.

The overall objective of this thesis is to uncover the factors associated with gait velocity following stroke. This research will add to the body of knowledge in the area of gait rehabilitation through the determination of associations between post-stroke impairment and specific gait parameters. Importantly, this research has the potential to inform clinical practice for the development of combined gait rehabilitation therapies in order to increase the potential gait velocity among individuals after stroke. This in turn, is expected to positively influence independent mobility within the community.
Figure 1: Predictive model of potential factors associated with maximum gait velocity following stroke.
2.0 Background

2.1 Prevalence of stroke

Stroke is a leading cause of adult neurologic impairment. As a result of improved acute care following stroke, more individuals are living with the effects of stroke than ever before. Therefore, the importance of stroke recovery-related research has never been greater. Within Canada there are approximately 50,000 strokes per year (Statistics Canada, 2011). According to the Heart and Stroke Foundation of Canada (2013), 315,000 Canadians are living with the effects of stroke, which placed a burden on family, friends, care givers, and the health care system. Each year, stroke costs the Canadian economy approximately $3.6 billion in hospital costs, physical services, decreased productivity, and lost wages (Public Health Agency of Canada, 2009).

2.2 Post-stroke symptoms

Following stroke, individuals can experience any number of impairments including; impaired motor function, sensory deficits, abnormal tone, perceptual deficits, cognitive limitations, aphasia, and depression (Duncan, 1994). Each of these symptoms impose challenges to performing activities of daily living. Even the recovery profiles, which are typified by rapid recovery up until approximately 3 months post-stroke, followed by very gradual improvement or a plateau in functional recovery (Kwakkel et al., 2006) are sensitive to factors such as severity (Patterson et al., 2007) and lesion location (Alexander et al., 2009). This heterogeneity makes treatment, research and rehabilitation difficult to generalize across individuals.
2.3 Importance of post-stroke gait

While stroke results in a wide range of functional limitations, none are more paramount than motor function, or more specifically, walking. Improved walking is the most frequently stated outcome goal for individuals with stroke during rehabilitation (Bohannon et al., 1988), as it greatly impacts independence and community participation (Perry et al., 1995; Schmid et al., 2007). Our daily lives necessitate a certain level of mobility to walk, either in the home or out in the community. Within these environments, individuals require an ability to regulate and maximize gait velocity in response to various environmental cues. Individuals with stroke are often unable to meet these requirements. The inability to appropriately optimize gait velocity can lead to challenges to safety (i.e., crossing the street) and social participation (i.e., inability to accompany friends on a walk). Individuals who develop inability to walk within the community are often housebound, leading to social isolation and depression (Ada et al., 2009).

2.4 Gait characteristics after stroke

Gait after stroke is characterized by a slowed velocity as well as temporal and spatial asymmetry (Patterson et al., 2012). Asymmetry is important clinically as it demonstrates imbalances and compensations due to impairments and may provide some insight into the underlying control of gait (Patterson et al., 2012). However, no clear evidence exists to suggest that symmetry enhances gait velocity or independence. A study by Teixeira-Salmela et al. (2001) found that symmetric patterns were unrelated to gait performance in chronic stroke participants. In contrast, while the use of gait velocity to predict community ambulation has been argued, van de Port et al. (2008) found gait velocity to be the most discriminative measure.
of community walking. Spatiotemporal characteristics of gait can be measured using kinetic and kinematic measurement tools, and muscle activity has also been used with the help of electromyography (Berger et al., 1984; Knutsson & Richards, 1979; Peat et al., 1976).

Research focusing on the stroke-related factors that relate to gait velocity have revealed there to be numerous possible factors. Gait velocity has been reported to be associated with several characteristics, including: balance (Witte & Carlsson, 1997), hip, knee, and/or ankle strength (Hsu et al., 2003; Olney et al., 1991), muscle tone (Knutsson & Richards, 1979), sensation (Keenan et al., 1984), and age (O'Brien et al., 1983). However, there is little consensus regarding the extent of association between these factors and gait velocity. One issue is that the majority of this research has examined the modifiers of gait velocity at preferred gait velocity rather than at maximum velocity or both preferred and maximum together.

Maximizing gait velocity is necessary for various tasks while walking within the community. While preferred gait velocity is of obvious importance, its slowing may be a compensatory strategy for counteracting underlying impairment and control challenges. Therefore, the measurement of maximum gait velocity may better predict social participation and community integration post-stroke. In addition, preferred and maximum gait velocity requires the individual to draw on different functional resources in order to complete the task. Due to the inherent differences between preferred and maximum gait velocity, research involving both velocities could reveal those post-stroke impairments which uniquely predict each velocity.
2.5 Relationship of cadence, step length and velocity in healthy adults

While gait velocity is an important post-stroke gait characteristic, the contributions of cadence and step length to velocity reveal the specific strategies that are used to achieve a particular velocity. There is an expected association between step length, cadence and gait velocity. A study by Andriacchi et al. (1977) found that cadence and step length vary linearly with gait velocity. Therefore, a change in either parameter would result in a change in velocity. Healthy individuals typically choose a strategy which allows for the most efficient gait pattern (cadence/step length relationship) at a particular velocity. Indeed, any increase in gait velocity requires an increase in energy expenditure (Kirtley et al., 1985); however, efficiency in the gait pattern can be obtained when increased step length is used to increase velocity (Thaut et al., 1997). Older adults demonstrate an even higher need to maintain efficiency and preserve energy (Cavagna & Franzetti, 1986; Murray, 1967); but, neurological, medical, psychological, or biomechanical diseases (Imms & Edholm, 1981; Jansen et al., 1982; Larish et al., 1988) alter the strategy used to optimize velocity during gait. More specifically, ageing is characterised by a decrease in gait velocity brought on by shorter stride length and increased cadence (Ostrosky et al., 1994). Similar factors may contribute to slowed velocity after stroke; although, further study of the causes of slowed velocity in stroke is required, given the complexity of post-stroke gait.

2.6 Importance of cadence-to-step length ratio after stroke

Current literature within the healthy population has shown decreased height (leg length) (Cunningham et al. 1982), increased stiffness and/or reduced muscular power at the
hips, knees, and ankles, and psychological factors (Elble et al., 1991) are all negatively correlated to cadence and step length. However, other than one report describing the impact of hip flexor/knee extensor weakness on gait velocity after stroke (Bohannon, 1986), there is considerably less information on these factors within the stroke population. This is surprising considering that individuals with stroke walk at a slower velocity using a higher cadence and a lower step length than their healthy counterparts (Jonsdottir et al., 2009).

The shift towards increased cadence and decreased step length after stroke may be a direct result of the numerous physical impairments resulting from the neurological injury. Since our knowledge of the impairments relating to gait velocity, cadence, and step length are still relatively unclear, classifying the strategy one uses to achieve a particular velocity (i.e. the relationship between cadence and step length), may give researchers and clinicians insight to the underlying control of gait which may not simply be revealed by the measure of velocity alone or by the component impairments.

2.7 Rationale and objectives

The global objective of the current project was to uncover the factors associated with gait velocity post-stroke with a particular emphasis on: 1) **maximal** gait velocity and the **capacity** to increase velocity; and 2) the **strategy** one uses to achieve this velocity. Over the long term, a better understanding of the person-specific factors that influence gait velocity may help guide therapeutic approaches used to enhance maximum gait velocity after stroke.

To address the overall objectives, the current thesis focussed on two studies. The objectives of the first study were to: 1) determine the association between specific post-stroke
characteristics and their differential role on preferred and maximum gait velocity; and 2) address the factors that relate to the capacity to increase gait velocity (i.e. the difference between preferred and maximum). As noted previously, research has investigated the relationship between some impairments and gait velocity (weakness, hypertonicity, sensory deficits, balance control problems) (Pang et al., 2005; Rosen et al., 2005). However while these studies have looked at preferred or maximum gait velocity, few of them have looked at both gait velocities or linked these impairments to the ability to change gait velocity (capacity).

Upon identifying the physical factors that pose barriers to maximizing gait velocity, we sought to attain knowledge on how individuals with stroke achieve a particular velocity. We know that gait velocity necessitates an increase in cadence, step length, or some combination of the two. Individuals with stroke have been found to modify cadence rather than step length to increase gait velocity (Jonsdottir et al., 2009). The reasons for this are not well known, so our second study set out to uncover why individuals with stroke rely on cadence rather than step length to achieve a particular velocity.

Because a number of stroke-related physical impairments affect maximum gait velocity, it is reasonable to assume that many of these factors would also uniquely influence either cadence and step length. Since the impairments affecting each individual are inherently different, the resulting strategy one uses in order to achieve a particular velocity should also be different. We believe that examination of this strategy (cadence/step length) will offer insight as to the control challenges of gait following stroke. These control challenges are not exposed through the measurement of velocity or impairment on their own (the objective of the first study) and therefore require a follow up study to build on the first. With this, the objective of
the second study was to characterize the strategy one uses to achieve a particular velocity and compare this to the strategy found in healthy individuals. We also wanted to establish whether there was a relationship between cadence, step length, strategy, and post-stroke impairment. Characterizing the strategy used to achieve a particular velocity and identifying the impairments that could be limiting the ability to achieve maximum velocity are important steps towards the eventual development of rehabilitation strategies aimed at enhancing mobility.
3.0  Study 1: Factors relating to preferred and maximum gait velocity after stroke

3.1  Abstract

Slowed walking is a common consequence of stroke. This decrease in gait velocity is believed to be a result of acquired physical impairments; however, there is no consensus on the specific physical impairments that relate to a slowed velocity. An understanding of the determinants of slowed walking will help to inform best approaches to increase gait velocity after stroke. This study sought to establish the determinants of both preferred and self-selected maximum gait velocity and to identify the predictors of an individual’s capacity to increase gait velocity. This involved secondary analysis of a database of stroke recovery and included 76 participants for analysis. Gait measures were collected using a pressure sensitive mat. Stepwise linear regression and correlation analysis was used to establish the determinants of gait velocity. Variables related to the following domains were included: functional balance, lower limb motor impairment and spasticity, age, gender, and time post-stroke. While several factors were related to gait velocity and ability to change, such as age and ankle spasticity, functional balance was the single most predictive impairment affecting individuals with stroke. Preferred velocity was highly correlated with self-selected maximum velocity ($r = .90$). The results emphasized the importance of assessment and recovery of balance control as important determinant of walking capacity.
3.2 Introduction

Stroke can result in various motor, perceptual, cognitive, sensory, and communication deficits, as well as abnormal tone and depression (Duncan, 1994). One of the challenges that can profoundly restrict independence and participation is stroke-related mobility impairment (Perry et al., 1995; Schmid et al., 2007). After experiencing a stroke, two out of three individuals are left with some level of gait dysfunction (Jorgensen et al., 1995), which can be associated with weakness, spasticity, and sensory/perceptual deficits (Patla & Shumway-Cook, 1999), elements that have been suggested to control function. The combined effects of these gait-associated impairments have a considerable impact on the capacity for independent mobility necessary for everyday tasks.

While the ability to walk independently is certainly a critical threshold for achieving community participation, for those able to walk, the capacity to walk more rapidly is important. While an individual may be able to walk independently, slow gait velocity can continue to limit activities in daily life, such as crossing the street, walking with friends, or walking in a crowded place, and is often associated with reduced overall activity and social participation (Ada et al., 2009; Perry et al., 1995; Schmid et al., 2007). Velocity is not the only important characteristic of post-stroke gait; however, it is a composite measure of capacity and has important implications for community participation. Given this importance, the current study is focussed on understanding the determinants of the capacity to increase gait velocity after stroke.

In considering the capacity to walk quickly, one must contemplate both ‘preferred’ gait velocity, as well as the ‘maximum’ or ‘fast as possible’ gait velocity. Slowing of gait velocity after stroke is likely an important compensatory strategy devised to counteract the underlying
control challenges. Thus, preferred gait velocity (which will be inherently slower than maximum velocity) may more strongly reflect these compensatory strategies, rather than revealing specific insight into the capacity to walk more rapidly when needed. In contrast, measuring maximum gait velocity by asking the participant to walk as quickly as possible may be a better predictor of social participation and community integration post-stroke, even if it is still influenced and/or limited by personal choice. The measure of maximum self-selected velocity may more accurately reveal walking capacity than preferred velocity. This is indirectly supported by studies that have revealed a modest or absent association between preferred and maximum gait velocity. Among those that reveal a significant association, preferred velocity accounted for only 32-41% of the variation in maximum velocity (Bohannon, 1992; Kollen et al., 2006). This leads to the possibility that there are important differences in the factors that influence measures of preferred and maximum gait velocity, and that investigations that key in on these determinants should focus on both preferred and maximum gait velocities.

It has been suggested that gait velocity is dependent on many characteristics, including balance (Witte & Carlsson, 1997), hip, knee, and/or ankle strength (Hsu et al., 2003; Olney et al., 1991), muscle tone (Knutsson & Richards, 1979), sensation (Keenan et al., 1984), and age (O'Brien et al., 1983). However, the variability in findings within individual impairment domains indicates that preferred and maximum velocities may be differentially affected by different post-stroke impairments. The balance sub-score of the Fugl-Meyer Assessment has been reported to be highly correlated with both preferred and maximum gait velocity (Nadeau et al., 1999); however, Suzuki et al. (1999) reported that postural sway was not a main determinant of maximum gait velocity. Using spasticity as an example, conflicting reports have identified the
presence (Knutsson & Richards, 1979) or absence (Bohannon, 1987) of a negative correlation between ankle plantar-flexor spasticity and gait velocity, suggesting that increased ankle plantar-flexor spasticity may lead to a slowed gait velocity, especially at self-selected maximum. Further impacting the interpretation of these results is the observation that the previous work, with a few exceptions, focus on either preferred or maximum gait velocity, but not both.

This study aims to address the relationship between post-stroke impairment and gait velocity. The primary objective is to determine the individual factors that relate to preferred and maximum gait velocity, as well as the factors that uniquely predict the capacity to increase gait velocity (i.e. the difference between preferred and maximum). As a result of the inherent differences in the biomechanical properties of preferred and maximum gait velocity, the factors affecting each velocity are expected to differ from each other. Both balance (Witte & Carlsson, 1997) and muscular strength (Hsu et al., 2003; Taylor-Piliae et al., 2012) have been reported within the literature as important determinants of both preferred and maximum gait velocity. Therefore, we hypothesize that lower limb motor impairment (a composite measure which includes the influence of muscular strength) and functional balance will be significant predictors of both preferred and maximum gait velocity as well as capacity. In addition, even with the conflicting evidence surrounding the impact of spasticity on gait velocity, due to its velocity dependent nature, we hypothesize spasticity will have a negative relationship with self-selected maximum velocity and capacity. In contrast, due to the overpowering relationship of post-stroke impairment over age-related changes in gait velocity, age is not expected to be a significant predictor of either gait velocity. The current study will try to clarify these
associations using widely accessible clinical measurement tools in order to increase the relevance of the results to clinical practice.

3.3 Methods

3.3.1 Participants

The present study involved a retrospective analysis of data extracted from the Heart and Stroke Foundation Centre for Stroke Recovery Longitudinal Database. The database contains outcomes from standardized motor and cognitive assessments conducted across 4 hospitals (one acute care and three rehabilitation hospitals). The data were collected at repeated time points up to 2 years after stroke. The study received approval by each institution’s Research Ethics Board and participants provided written informed consent prior to participation.

The current cross-sectional study limited the focus to data from the first visit in which participants completed the gait component of the larger assessment. Data were included from participants who were able to walk independently for 4-meters without the use of a gait aid. Any individuals who had bilateral impairment or medical conditions influencing gait (e.g. Parkinson’s disease, knee or hip replacement) were excluded. Of the 223 individuals available at the time of analysis a total of 76 participants met the criteria. Of the 147 participants excluded, 85 had no walking trials without a gait aid; 12 had bilateral impairment; 6 had a co-morbidity affecting gait; and 44 had missing data for one or more outcomes.

3.3.2 Measures

Gait variables were collected using the GAITRite® electronic walkway, a 4 metre-long portable walkway used to measure spatial and temporal parameters of gait. The GAITRite® has been shown to have high concurrent validity and test-retest reliability for gait speed (ICC (2,1) =
Participants were asked to perform 2 different tasks: 1) walk at self-selected preferred pace (preferred) and 2) walk as fast as possible (maximum). Three trials were performed for each task, with the fastest trial for each task condition being used for analysis as it represents the highest level of function for the individual. Capacity, defined as the ability to change one’s velocity from preferred to a self-selected maximum, was calculated as both an absolute value (maximum - preferred) and a relative value ((maximum – preferred)/preferred x 100). Cadence and step length were also collected using the GAITRite® electronic walkway.

Clinical assessments were performed by experienced physiotherapists. Motor impairment was assessed using the leg and foot sub-scores of the Chedoke-McMaster Stroke Assessment (CMSA), which has been found to be both reliable and valid (Gowland et al., 1993). Each sub-section of the CMSA is measured on a 7-point scale, which corresponds to the seven stages of motor recovery (Brunnstrom, 1970). Functional balance was assessed using the Berg Balance Scale (BBS). The BBS was developed to assess balance in elderly, community-dwelling individuals. The scale consists of 14 items scored on a scale from 0-4 with a total possible score of 56. The BBS has been reported to be valid and reliable in individuals with stroke (Berg et al., 1995). Spasticity was determined using the Modified Ashworth Scale (MAS) assessed for the knee extensors and the ankle plantarflexors. The MAS uses a 6-point scale (range 0-4). The MAS has excellent validity (Lin & Sabbahi, 1999), adequate intra-rater reliability, though inter-rater reliability for the lower extremity is poor (Blackburn et al., 2002).

3.3.3 Data analysis
Pearson correlation analysis was performed to account for inter-relationships between impairment measures to establish individual relationships between impairment level and velocity (self-selected maximum, preferred, and capacity). Paired t-test was used to determine if the increase in gait velocity within participants was statistically significant. A stepwise linear regression was conducted to determine the best combination of factors relating to preferred and maximum gait velocity and both measures of capacity. Eight variables were added to the regression model as possible predictors (BBS, leg and foot sub-scores of the CMSA, the knee, gastrocnemius, and soleus sub-scores of the MAS, age, and time post-stroke). For all statistical analyses, alpha was set at 0.05. Data were analyzed using SAS 9.3 for Windows (SAS Institute, Cary, North Carolina).

### 3.4 Results

#### 3.4.1 Patient characteristics

The data from seventy-six participants (44 male, 32 female) were included for analysis in this study. Complete participant characteristics are summarized in Table 1.

#### 3.4.2 Clinical characteristics

The primary clinical indices in the present study were Berg Balance Scale (BBS), Chedoke McMaster Stroke Assessment (CMSA), and Modified Ashworth Scale (MAS). Overall, the mean BBS for stroke participants was 49.6 (out of 56) (SD 8.4), with a range of 11 to 56 (Figure 2a). The median CMSA was 6 and 5 for the leg and foot respectively. The values ranged from 2 to 7 (Figure 2b). The MAS scores ranged from 0 to 2 (out of 4) with the median being 0 for all sub-scores (knee, gastrocnemius and soleus). Overall, 55 participants had a MAS of 0, and 21 participants had a MAS of 1 or greater for one or more of the sub-score (Figure 2c).
Table 1: Participant demographics and stroke characteristics. Values are presented as mean ± standard deviation (SD) and range.

<table>
<thead>
<tr>
<th>Characteristics (N=76)</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>62.2 ± 11.98</td>
<td>28-89</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>168 ± 10</td>
<td>147-187</td>
</tr>
<tr>
<td>Sex, number (M/F)</td>
<td>44/32</td>
<td>N/A</td>
</tr>
<tr>
<td>Time post-stroke (months)</td>
<td>8.1 ± 18.4</td>
<td>0.3-104.3</td>
</tr>
<tr>
<td>Affected hemisphere, number (%)</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>28 (36.8)</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>44 (57.9)</td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td>1 (1.3)</td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td>3 (4.0)</td>
<td></td>
</tr>
<tr>
<td>Paretic side, number (%)</td>
<td>N/A</td>
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</tr>
<tr>
<td>Right</td>
<td>46 (60.5)</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>30 (39.5)</td>
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<tr>
<td>Stroke type, number (%)</td>
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</tr>
<tr>
<td>Ischemic</td>
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<tr>
<td>N/A or missing</td>
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</tbody>
</table>

Table 2: Association between clinical measures and patient characteristics. Pearson correlation coefficients are presented for the associations between impairment measures (MAS, CMSA), functional measures (BBS), and patient characteristics. Statistically significant correlations found between Berg Balance Scale and sub-scores of Chedoke-McMaster Stroke Assessment (CMSA), as well as between sub-scores of Modified Ashworth Scale (MAS). Significance denoted by (* = p<0.05) or (**) = p<0.001).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Berg Balance Scale</th>
<th>CMSA Leg</th>
<th>CMSA Foot</th>
<th>MAS Knee</th>
<th>MAS Gastrocnemius</th>
<th>MAS Soleus</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSA Leg</td>
<td>0.51**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMSA Foot</td>
<td>0.44**</td>
<td>0.76**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAS Knee</td>
<td>-0.03</td>
<td>-0.13</td>
<td>-0.24*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAS Gastrocnemius</td>
<td>0.03</td>
<td>-0.08</td>
<td>-0.17</td>
<td>0.57**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAS Soleus</td>
<td>-0.07</td>
<td>-0.20</td>
<td>-0.24*</td>
<td>0.62**</td>
<td>0.69**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>0.01</td>
<td>0.08</td>
<td>0.12</td>
<td>-0.08</td>
<td>-0.17</td>
<td>-0.28*</td>
<td></td>
</tr>
<tr>
<td>Time Post-Stroke</td>
<td>0.23*</td>
<td>0.28*</td>
<td>0.29*</td>
<td>-0.01</td>
<td>-0.05</td>
<td>-0.06</td>
<td>0.04</td>
</tr>
</tbody>
</table>

There were statistically significant correlations between many of the clinical measures and patient characteristics (Table 2). The BBS was positively correlated with the CMSA leg ($R^2=0.51; P=<0.0001$) and foot ($R^2=0.44; P=<0.0001$), and time post-stroke was significantly
correlated with the BBS ($R^2=0.23; P=0.04$) and CMSA leg ($R^2=0.28; P=0.01$) and foot ($R^2=0.29; P=0.01$). The CMSA foot measure had a statistically significant correlation with the MAS soleus ($R^2=-0.24; P=0.04$) and knee ($R^2=-0.24; P=0.04$) scores.

Figure 2: Distribution of impairment scores (impairment increases from left to right). Number of participants with a particular score were reported for (A) Berg Balance Scale, (B) Chedoke-McMaster Stroke Assessment, and (C) Modified Ashworth Scale (n = 76).
3.4.3 Gait velocity

Average preferred and self-selected maximum gait velocity was 0.81 m/s (range 0.11-1.46 m/s) (SD 0.32 m/s) and 1.22 m/s (range 0.11-2.23 m/s) (SD 0.5 m/s), respectively (Table 3). The distributions of the gait velocities for preferred (A), self-selected maximum (B) and absolute capacity (C) are displayed in Figure 3. The within-subject differences between preferred and self-selected maximum gait velocity were, on average, 0.41 m/s (SD 0.26). Maximum gait velocity was significantly greater than preferred gait velocity (t(75)=13.92, p<.0001). In addition, the absolute and relative capacity values were 0.41 m/s (SD 0.26 m/s) and 52% (SD 33%) respectively. It is noteworthy that there was a positive correlation ($R^2=0.9; P=<0.0001$) between preferred velocity and highest attainable self-selected maximum velocity.

Table 3: Gait characteristics of stroke participants. Values are presented as mean ± standard deviation (SD) and range.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preferred Mean ± SD</th>
<th>Range</th>
<th>Maximum Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m/s)</td>
<td>0.81 ± 0.32</td>
<td>0.11 - 1.46</td>
<td>1.22 ± 0.50</td>
<td>0.11 - 2.23</td>
</tr>
<tr>
<td>Cadence (steps/sec)</td>
<td>0.92 ± 0.13</td>
<td>0.35 - 1.25</td>
<td>0.15 ± 0.26</td>
<td>0.35 - 1.69</td>
</tr>
<tr>
<td>Step Length (m)</td>
<td>0.51 ± 0.14</td>
<td>0.18 - 0.93</td>
<td>0.61 ± 0.17</td>
<td>0.18 - 1.01</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Relative (%)</td>
<td>52 ± 33</td>
<td>0 - 182</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Absolute (m/s)</td>
<td>0.41 ± 0.25</td>
<td>0 - 1.15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4.4 Univariate analysis

A univariate analysis between our dependent and independent variables revealed functional balance ($R^2=0.51-0.58$) and both sub-scores of the CMSA (leg $R^2=0.32-0.41$; foot $R^2=0.31-0.38$) to be predictors of preferred and maximum gait velocity, and absolute capacity. Time post-stroke was also a statistically significant predictor of preferred ($R^2=0.27$) and maximum ($R^2=0.28$) gait velocity.
When combining the variables to determine the degree of variance in gait velocity accounted for, only 34% of the variability in preferred and 43% of the variability in maximum gait velocity was accounted for. Stepwise regression found functional balance (BBS) to be the only statistically significant variable for both preferred ($R^2=0.26; P<0.0001$) and maximum gait velocity.

### 3.4.5 Multivariate regression

Figure 3: Distribution of walking velocities by number of participants. Greater range can be observed within maximum gait velocity than preferred gait velocity. While many individuals were able to increase gait velocity from preferred, some individuals lack the resources to accomplish this. Distributions for A)
(R²=0.34; P=< 0.0001) velocity. The 8-variable model and the BBS in stepwise regression accounted for more of the variability in self-selected maximum gait velocity than preferred gait velocity (Table 4).

**Table 4:** Results of stepwise multivariate regression. Only functional Berg Balance Scores (BBS) were significantly associated with the specific measures of gait velocity. Direction of relationship, R-square and p-value for the significant variable(s), as well as the combined R-square of the model (\( R^2 \)) are reported.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Statistically Significant Variable(s)</th>
<th>+/-</th>
<th>( R^2 )</th>
<th>P</th>
<th>( R^2 ) Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred Velocity</td>
<td>BBS</td>
<td>+</td>
<td>0.26</td>
<td>&lt;.0001</td>
<td>0.34</td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td>BBS</td>
<td>+</td>
<td>0.34</td>
<td>&lt;.0001</td>
<td>0.43</td>
</tr>
<tr>
<td>Capacity (Absolute)</td>
<td>BBS</td>
<td>+</td>
<td>0.26</td>
<td>&lt;.0001</td>
<td>0.32</td>
</tr>
<tr>
<td>Capacity (Relative)</td>
<td>BBS</td>
<td>+</td>
<td>0.08</td>
<td>0.0121</td>
<td>0.22</td>
</tr>
</tbody>
</table>

When relative capacity (percent change in velocity between preferred and maximum) was assessed using the same model, only 22% of relative capacity was explained using the collective predictive capacity of all variables. BBS was revealed as the only statistically significant variable, accounting for 8% (P=0.0121) of the variance. For absolute capacity (total change in velocity between preferred and maximum), BBS accounted for 26% (P<0.0001) of the variance and was the only statistically significant variable, with an additional 6% of additional variance accounted for through the combined R-squared calculation using the full model.

### 3.5 Discussion

The primary focus of the study was to quantify the determinants of gait velocity and capacity to increase gait velocity. With respect to the factors that predicted gait velocity and the capacity to increase gait velocity, functional balance, as measured by the BBS, was found to be the only statistically significant factor. The predictive capacity of the variables within the model was low, as only 23-34% of the variance was accounted for.
The gait velocities (mean and associated variability) in the current study were faster and had a larger range of values than other studies focused on walking after stroke (Beaman et al., 2010; Bohannon, 1992). Gait velocity in this study was on average slower at both preferred (0.81 m/s, SD 0.32 m/s) and maximum (1.22 m/s, SD 0.5 m/s), than gait velocity of healthy age-matched individuals for both velocities (1.38 m/s, SD 0.17 m/s; 2.16 m/s, SD 0.32 m/s) (Bohannon, 1997). Also, consistent with previous research, in spite of variation in capacity to increase velocity across individuals, preferred and maximum gait velocities were highly correlated ($R^2 = 0.9$) with each other. In the non-stroke population, Cunningham et al. (1982) noted a correlation of 0.83 between preferred and maximum gait velocity. Among stroke survivors, Bohannon (1992) and Kollen et al. (2006) reported a similar correlation and suggested equations to calculate maximum velocity using preferred velocity. While it is possible to estimate maximum from preferred, the variability across individuals makes this difficult to generalize, particularly after stroke. Within the current study, the wide range of velocity change scores between preferred and maximum gait velocity demonstrates the variability of velocity between individuals with stroke.

Within the healthy population, the ability to increase velocity beyond a preferred gait velocity is common and has also been reported in individuals post-stroke (Bohannon, 1989). This ability to change, while found to be statistically significant within our group as a whole, was not seen in each participant. The capacity to increase velocity was not unique to individuals with a slow preferred gait velocity and therefore was not simply a product of a low preferred gait velocity. Indeed, our sample included individuals whose preferred gait was in the upper band for reported velocities (Brandstater et al., 1983; Knutsson & Richards, 1979; Olney et al.,
In fact, it appears most likely that the capacity to increase reflects, to some extent, limitations in the reserves available to each individual. Since the stroke population is such a heterogeneous population, the reason for this variability in the ability to access reserves can only be speculated. It could come down to psychological components, decreased balance, lower limb sensory impairment, or the ability to compensate for various impairments with other muscle groups. The group score which is commonly reported is capable of misrepresenting this change and could explain the finding that individuals with stroke have within them the functional resources to significantly increase gait velocity. This could bring into question the conclusions of studies that looked at the individual change scores without comparing them individually or to a minimal detectable change score.

Impaired balance was associated with slower gait velocity for preferred and maximal walking as well as the capacity to increase velocity. This finding is consistent with previous research which found various measures of balance to be significant predictors of overall gait performance (velocity, cadence, independence, and asymmetry) (Bohannon, 1987). Studies have also pointed to the role that functional balance and balance confidence play during gait (Rosen et al., 2005). Multivariate analysis confirmed the relationship between balance and ability to increase velocity (absolute capacity) and the proportional change in velocity (relative capacity) among individuals with stroke. Balance alone accounted for approximately 8-26% of the variance within this model. Although the results of our study are convincing regarding the role of functional balance, the 8-variable model did account for 43% of the variance in gait velocity highlighting the multivariate nature of the determinants to gait velocity. For example, within the group with the highest attainable BBS score, there was still a wide range of
velocities, 0.77-1.46 m/s and 1.05-2.14 m/s for preferred and self-selected maximum velocity respectively. This suggests that while all the variables are responsible for some contribution to the variance in gait velocity, there remain other potentially important factors influencing gait velocity.

Contrary to our hypotheses, lower limb impairment and spasticity were not found to be statistically significant predictors of preferred or self-selected maximum velocity. The absence of an association between maximal gait velocity and spasticity was surprising. Even though the role of spasticity in gait has been debated in the literature (Knutsson & Richards, 1979); (Bohannon & Andrews, 1990), we anticipated the velocity dependant nature of spasticity to be more pronounced as velocity increased, leading to a decrease in overall plantar-flexor propulsion and an inverse relationship with maximum velocity. Our findings are in agreement with Bohannon et al (1990) who found no relationship between ankle plantar-flexor spasticity and gait velocity. However, the absence of a significant association may be associated with the low range of spasticity measured in this study (Modified Ashworth Scores: 0-2/4) and the low number of individuals in the study with spasticity (n=21). In addition, the individuals found to be able achieve a relatively high maximum gait velocity were those without any measureable spasticity in the lower limb. The reliability and validity of the MAS has also been questioned. This includes its ability to distinguish between different types of hypertonia (spasticity, contracture, and elevated tone) (Patrick & Ada, 2006) and the reliability of the measure for the lower limb (Pandyan et al., 1999; Sloan et al., 1992). Patrick et al. (2006) found that the MAS was unable to differentiate between spasticity and contracture. The current focus was directed to ankle and knee, so it is quite possible that spasticity at the hip may have a more profound
influence of maximum over ground gait velocity by influencing swing speed. In addition, it is also possible that those with ankle spasticity may be able to compensate using the hip flexors as opposed to relying on the plantar-flexors (Nadeau et al., 1999). As a result, while the current group analysis did not support a relationship between spasticity and velocity, it remains quite possible that this relationship is important in individuals with a high degree of hypertonicity.

The composite nature of and strong correlation between both the BBS and the CMSA could have contributed to the absence of lower limb impairment as a statistically significant variable in gait velocity. However, even when the BBS was removed from the model, the CMSA did not surface as a significant predictor. In contrast to the current observations, previous research by Hsu et al. (2003) found that hip flexor and knee extensor weakness was a significant predictor of gait velocity. This difference in studies may be associated with the specific instruments and measures of impairment. The CMSA is not a direct measure of either leg extension strength or ankle plantar-flexor strength, this may account for the weaker association with gait velocity as compared to a measure that was primarily assessing strength.

Previous research done by O'Brien et al. (1983) found common predictors of gait velocity in healthy individuals, such as gender and age. However, these were not associated with gait velocity in individuals post stroke, being attributed instead to the impairments unique to stroke and post-stroke gait (Bohannon, 1986). In contrast to healthy individuals, the neurological disturbances that accompany stroke may mask the influence of factors such as gender and age normally found to be significant. Predictors of gait velocity in healthy individuals are related to a number of different variables (e.g. height, weight, age, gender, and lower limb muscle strength). Bendall et al., (1989) reported height, plantar-flexor strength, and
presence of leg pain were the main factors influencing gait velocity, yet these only accounted for approximately 44% of the variance in their model. Another study by Bohannon et al. (1996) found that despite the highly significant correlations within their regression equation, only a small percentage of the variance in both preferred and maximum gait velocity was accounted for (13% and 21% respectively). This demonstrates the large variance not accounted for by seemingly significant variables, even within the healthy population. Therefore, not only are individuals with stroke constrained by individual difference within their general gait pattern, but they are also hindered by the complex effects of post-stroke impairment. This interplay may be better able to explain the variance found in preferred and maximum gait velocity, as well as their capacity to change gait velocity.

While the current model accounted for 26-34% of the variability, there remains the important question, as in the healthy population, of the other potential contributors that may relate to selected gait velocity and the capacity to increase. It is very likely, even with the obvious influence of functional balance within this study and the literature, that there are additional factors influencing variability in gait velocity post-stroke. Some of the unaccounted variability may be associated with the lack of specific impairment measures, as composite measures such as the BBS and CMSA may overshadow these. Variables such as sensory input, signal conduction speed, psychological state (e.g. fear/anxiety), flexion/extension strength at the hip, knee, and ankle, active joint range of motion, and spasticity at the various joints may need to be measured individually within research to get a full picture of impairments affecting gait velocity post-stroke. Due to the apparent inability of the current variables to predict the
variability within the model, additional factors along with the influence of pre-existing motor patterns need to be considered in future research.
4.0 Study 2: Developing a strategy: Relationship between cadence-to-step length ratio, velocity, and impairment post-stroke

4.1 Abstract

Following stroke, gait velocity is slowed and often is lower than what is required for independent community walking. Since velocity is a product of cadence and step length, the specific capacity to increase velocity depends on the ability to increase these two gait parameters. However, the strategy of using cadence or step length to increase gait velocity may be influenced by stroke-specific impairments. Therefore, an individual's capacity to increase gait velocity may be uniquely influenced by the ability to increase either cadence or step length. The objective of this study was to determine the cadence/step length characteristics used to achieve specific gait velocities comparing between the stroke and healthy population. In addition, the study sought to determine the relationship between post-stroke impairment and the cadence/step length strategy. A retrospective analysis was conducted using data from the Heart and Stroke Foundation Centre for Stroke Recovery Rehabilitation Affiliates Database. A total of 71 participants with stroke were included in the analysis and compared to the data from 89 healthy individuals. Gait measures (cadence/step length ratio) and gait velocity were calculated from data collected using a GAITRite® Walkway. Clinical outcome measures (BBS, CMSA, MAS) and demographics were also compared across preferred and maximum velocity. While individuals with stroke walked at a slower velocity compared to healthy controls (0.85 m/s vs. 1.19 m/s), there was no statistically significant difference in the cadence/step length ratio (i.e. strategy) adopted by each group. Functional balance was found to be a statistically
significant predictor of step length at both preferred ($R^2 = 0.09$, $p = 0.007$) and maximum ($R^2 = 0.16$, $p = 0.0006$) gait velocity. While the mean ratio was similar between groups and tasks, the functional resources available to increase gait velocity (variability between tasks) following stroke were different. The reliance on cadence to increase gait velocity post-stroke, and the positive correlation between step length and balance may reveal balance and step length to be two of the limiting factors to maximizing gait velocity.

4.2 Introduction

Recovery of independent walking after stroke is an important determinant of functional independence and participation in activities of daily life (Ada et al., 2009; Perry et al., 1995; Schmid et al., 2007). Much attention has been directed towards gait velocity as an important metric of recovery (Goldie et al., 1996); however, there is little gain in gait recovery after the 3-6 month mark post-stroke (Lim et al., 2013). This apparent plateau may reveal limitations to an individual’s ability to achieve the necessary gait velocity for functional independence and optimizing participation within the community.

A common focus of study has been the measurement of one’s preferred gait velocity. This has been shown to be a sensitive and reliable index of change after stroke (Goldie et al., 1996; Patterson et al., 2007; Schmid et al., 2007). However, while preferred gait velocity can serve as a sensitive measure of recovery it does not simply predict success when returning to community activities (Lord et al., 2004). Importantly, the capacity to increase velocity when necessary in the community may be even more essential than preferred gait velocity. There are a number of studies that have revealed the ability of individuals with stroke to significantly increase their gait velocity above the preferred gait velocity, indicating a greater capacity to
walk faster than may be evident in the conventional gait assessment (Bohannon, 1989; Lamontagne & Fung, 2004). In spite of the ability to increase velocity, the maximum velocity is typically well below the preferred of healthy controls (Turnbull et al., 1995) and below that which is considered necessary for walking within the community, which varies from 0.8 m/sec to 1.2 m/sec (Hill et al., 1997; Lerner-Frankiel et al., 1986; Perry et al., 1995). While it is not necessary that individuals walk faster all the time, individuals require the capacity to safely and effectively increase velocity when it is appropriate. As a result, the aim of the present study is directed towards better understanding one’s capacity and strategy for increasing gait velocity after stroke.

The focus of this work is related to the strategies that are adopted when individuals with stroke attempt to increase gait velocity. To modify gait velocity, one can independently alter either cadence, step length, or some combination of the two. An expression of this difference in strategy is the cadence-to-step length ratio (steps/sec/m/step). Changes in the ratio reflect differences in the relative contribution in the use of cadence or step length when changing gait velocity. The increase in gait velocity from preferred to maximum following stroke relies considerably on more cadence versus step length (Jonsdottir et al., 2009). This strategy is opposite to the strategy that is used by healthy individuals (Bayat et al., 2005; Kramers de Quervain et al., 1996). While velocity is a useful index of recovery, we propose that an understanding of the associated strategy, assessed through this ratio, is also important. Therefore, an increase in velocity which relies heavily on cadence may be due to the fact that increases in stride length are compromised by certain post-stroke impairments. Such
understanding may begin to help inform about the barriers to faster gait velocity and potential targets for therapies to augment gait velocity.

It has been shown that after stroke, the reduction in preferred, and even more importantly maximum gait velocity, may result from a number of factors (weakness, hypotonicity, sensory deficits, VO$_2$, balance control problems, and confidence) (Pang et al., 2005; Rosen et al., 2005; Study 1). These factors in turn will likely uniquely influence ability to increase the speed of movement (cadence) or the amplitude of movement (step length). For example, step length could be directly influenced by functional balance which could limit the extent to which individuals choose to expand their base of support or the amount of time one is able to spend in single support during gait. Also, plantar-flexor hypertonicity may reduce the available range of motion around the ankle joint, limiting step length and therefore increasing the subsequent role of cadence to increase gait velocity. Impairment-specific influences on cadence or step length are likely to subsequently influence the capacity and the strategy for increasing velocity after stroke. In this way, we believe that the measure of cadence/step length ratio may be able to provide insight into the underlying challenges in the control of gait that are not simply revealed by the measure of velocity alone or by the component impairments.

To our knowledge, there is currently no research that has looked at a cadence-to-step length ratio and the relationship to gait velocity and impairment. The specific aims of this study are to characterize an index of strategy reflected by the cadence-to-step length ratio after stroke in comparison to healthy adults. In addition, the study sought to determine the relationship between cadence-to-step length ratio and post-stroke impairments. It is hypothesized that there will be significantly higher cadence/step length ratio in post-stroke
individuals when compared to healthy adults. It is anticipated that this difference will be
evident at both preferred and maximum velocity, but that the ratio will be greater at higher
velocities within this population. With respect to the relationship of cadence/step length ratio
and impairments, it is hypothesized that functional balance (measured by the Berg Balance
Scale) and lower limb motor impairment (measured with Chedoke-McMaster Stroke
Assessment) will be positively correlated with cadence/step length ratio. This latter hypothesis
is based, in part, on a previous study reporting lower limb strength to be strongly related to
step length (Hsu et al., 2003), as well as the assumption that individuals with poor functional
balance will minimize single-stance time, thereby decreasing step length and increasing
cadence. It is also predicted that an increase in plantar-flexor spasticity, as measured by the
Modified Ashworth Scale, will be associated with a increase in cadence/step length ratio as
individuals would be less inclined to increase their single support time to allow for longer step
lengths, leading to shorter, more frequent steps. The results of this study will provide clinicians
with more clinically relevant information that can be combined with our current knowledge of
impairment-based gait rehabilitation to positively affect someone’s ability to walk
independently within the community following stroke.

4.3 Methods

4.3.1 Participants

The data used for this secondary review came from three sources, including, the Heart
and Stroke Foundation Centre for Stroke Recovery Longitudinal Database (stroke), Sunnybrook
Research Institute (healthy older adults), and Toronto Rehabilitation Institute (healthy younger
Each study received ethics approval from their respective institutions. Prior to participation in each study, participants were required to provide informed consent.

The healthy younger dataset contained 21 participants while the healthy older dataset contained 68 participants. All healthy participants were included in the analysis. The stroke dataset contained 223 individuals with stroke who met the inclusion criteria with 152 being excluded for the following reasons: 85 due to the use of a gait aid; 12 because of the presence of bilateral impairment; 6 because of the presence of a co-morbidity affecting gait; 33 due to no maximum or no preferred velocity trial being completed; 16 because of missing outcome measures. This left a total of 71 participants for analysis.

4.3.2 Measures

Data for the current study were based on the first visit for each participant. All gait data, including velocity, cadence, and step length, were collected using a pressure sensitive mat (GAITRite® Electronic Walkway). The GAITRite® is a 4-metre-long portable mat which is used to assess various temporal and spatial parameters of gait. It has been shown to have high concurrent validity and test-retest reliability for gait speed (ICC (2,1) = 0.99), stride length (ICC (2,1) = 0.99), and cadence (ICC (2,1) = 0.99) (Bilney et al., 2003). Individuals were required to walk independently across this mat for a predetermined number of trials. Healthy participants underwent a single task condition, comfortable pace (preferred), while stroke participants underwent 2 task conditions: 1) walk at a comfortable pace (preferred) and 2) walk as fast as possible (self-selected maximum). The average number of trials for each condition was 3; the fastest of these was used for analysis as it represents the highest level of function for the
individual. Additionally, cadence-to-step length ratio (steps/sec/m/step) was calculated for analysis between groups.

Along with the gait data, the stroke dataset also contains outcomes from standardized assessments including, the Chedoke-McMaster Stroke Assessment (CMSA) (Gowland et al., 1993) for assessing motor impairment, the Berg Balance Scale (BBS) (Berg et al., 1995) as a metric of functional balance, and the Modified Ashworth Scale (MAS) (Blackburn et al., 2002) to measure spasticity at the knee and ankle joints.

The Chedoke-McMaster Stroke Assessment (CMSA) has been found to be both reliable and valid (Gowland et al., 1993). Each sub-section of the CMSA is measured on a 7-point scale, which corresponds to the seven stages of motor recovery (Brunnstrom, 1970). The Berg Balance Scale (BBS), our measure of functional balance, was developed to assess balance in elderly, community-dwelling individuals. The scale consists of 14 items scored on a scale from 0-4 with a total possible score of 56. The scale has been reported to be valid and reliable in individuals with stroke (Berg et al., 1995). Spasticity was determined using the the Modified Ashworth Scale (MAS). The MAS uses a 6-point scale (range 0-4). The MAS has excellent validity (Lin, F. & Sabbahi, M. 1999), adequate intra-rater reliability, though inter-rater reliability for the lower extremity is poor (Blackburn et al., 2002).

4.3.3 Statistical analysis

Descriptive statistics were used to characterize the study participants. Prior to test selection, univariate analyses were conducted on all variables to determine if data were normally distributed. Means analysis was used to test the hypothesis that there was a statistically significant difference in ratio and velocity at both preferred and maximum and
between individuals with stroke and healthy individuals. In order to determine the role of impairment on the cadence-to-step length ratio of individuals with stroke, Pearson correlation analysis of each variable, as well as stepwise linear regression was performed. Eight variables were included in the regression model as possible predictors (leg and foot sub-scores of the CMSA, BBS, knee extensors, gastrocnemius, and soleus sub-scores of the MAS, time post-stroke, and age). Alpha was set at 0.05 for all statistical analyses. SAS 9.3 for Windows (SAS Institute, Cary, North Carolina) was used for all statistical analyses.

4.4 Results

4.4.1 Participant characteristics

Data from seventy-one participants with stroke and eighty-nine healthy individuals were included in the analyses. The mean age of all stroke participants was 61.7 years (range 28-89), while the healthy individuals had a mean age of 65.2 years (range 22-94). For those individuals with stroke, the average time post-stroke was 8.6 months (range 0.2 – 105.7). A complete list of participant characteristics is presented in Table 5.

Table 5: Participant demographics for both stroke and healthy group. Values are presented as mean ± standard deviation (SD) as well as range.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Stroke (N=71)</th>
<th>Healthy (N=89)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>Age (y)</td>
<td>61.7 ± 12.0</td>
<td>28 - 89</td>
</tr>
<tr>
<td>Gender, number (M/F)</td>
<td>43/28</td>
<td>N/A</td>
</tr>
<tr>
<td>Time Post-Stroke (months)</td>
<td>8.6 ± 18.9</td>
<td>0.2 - 105.7</td>
</tr>
</tbody>
</table>

Within the stroke population, three clinical indices were utilized to measure impairment. These included the Berg Balance Scale (BBS), Chedoke McMaster Stroke Assessment (CMSA), and the Modified Ashworth Scale (MAS). Complete clinical information can be found on Table 6.
Table 6: Clinical characteristics for individuals with stroke (n = 71). Mean ± SD and range are reported for the Berg Balance Scale, while median and range are reported for the Chedoke-McMaster Stroke Assessment and Modified Ashworth Scale.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Sub-Score</th>
<th>Value ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berg Balance Scale</td>
<td></td>
<td>51 ± 6</td>
<td>28 - 56</td>
</tr>
<tr>
<td>Chedoke-McMaster Stroke Assessment</td>
<td>Leg</td>
<td>6</td>
<td>2 - 7</td>
</tr>
<tr>
<td></td>
<td>Foot</td>
<td>5</td>
<td>3 - 7</td>
</tr>
<tr>
<td></td>
<td>Knee</td>
<td>0</td>
<td>0 - 2</td>
</tr>
<tr>
<td>Modified Ashworth Scale</td>
<td>Gastrocnemius</td>
<td>0</td>
<td>0 - 2</td>
</tr>
<tr>
<td></td>
<td>Soleus</td>
<td>0</td>
<td>0 - 2</td>
</tr>
</tbody>
</table>

4.4.2 Gait characteristics

The average step length at preferred gait velocity was 0.65 m/step (range = 0.36-0.95 m/step) (SD = 0.11) and 0.53 m/step (range = 0.20-0.93 m/step) (SD = 0.13) for healthy and stroke, respectively. The average cadence for healthy and stroke individuals at preferred gait velocity was 1.83 steps/s (range = 1.45 -2.29 steps/s) (SD = 0.17) and 1.56 steps/s (range = 0.73-2.08 steps/s) (SD = 0.27), respectively.

As a result of the shorter step length (t(158) = 6.30, p<0.0001) and lower cadence (t(114.68) = 7.30, p<0.0001) of individuals with stroke as compared to healthy individuals, the group demonstrated a slower overall gait velocity. The mean preferred gait velocity of healthy participants was 1.19 m/s (SD 0.24), whereas the preferred gait velocity of individuals with stroke was 0.85 m/s (SD 0.29), a difference found to be statistically significant (t(158) = 8.16, P <0.0001). In addition, maximum gait velocity was 1.29 m/s (SD 0.45) in individuals with stroke. The distributions of all velocities are depicted on Figure 4.

4.4.3 Strategy (cadence-to-step length ratio)

The distribution of the cadence-to-step length ratio (steps/sec/m/step) between groups when plotted against velocity was highly variable (Figure 5). There was no statistically
significant difference between the distributions. The difference in the mean ratio used by individuals with stroke at preferred (3.07 (SD 0.63)) and maximum (3.24 (SD 0.83)), as well as healthy individuals at preferred (2.89 (SD 0.54)), measured using the cadence-to-step length ratio (steps/sec/m/step), was not statistically significant between groups or tasks. There was a wider range of values for ratio at maximum gait velocity (range 1.66-7.73) than preferred gait velocity.

**Figure 4:** Distribution of preferred and maximum gait velocity for stroke and healthy participants. Individuals with stroke walked at a slower average preferred gait velocity than their healthy counterparts. The range of values at maximum gait velocity was larger than at preferred gait velocity.
velocity (range 1.58-5.60) for individuals with stroke (Figure 6). This difference was found to be statistically significant ($P = 0.0206$).

Specifically within the group with stroke, the within-subject difference between the cadence-to-step length ratio (steps/sec/m/step) from preferred to maximum gait velocity (0.17 (SD 0.57)) was statistically significant ($t(70) = 2.49, P = 0.0152$).

![Figure 5: Relationship between cadence/step length ratio (steps/sec/m/step) and waking velocity (m/s) for healthy (preferred), and stroke (preferred and maximum walking velocity). At a given velocity, the distribution of cadence/step length ratio across groups is variable.](image)

4.4.4 Strategy and impairment

Univariate analysis was used to assess the associations between the various gait variables and patient clinical characteristics (Table 7). Functional balance and lower limb motor impairment were found to be significantly correlated with all gait variables except cadence/step...
length ratio. Time post-stroke was also significantly correlated with gait velocity, step length and ratio (preferred gait velocity).

Figure 6: Mean tendency and ratio distribution by group and task. Within the stroke group, the variance within individuals at maximum gait velocity was higher than that of individuals at preferred gait velocity, a difference which was found to be statistically significant. There was no statistically significant difference in means between groups or tasks.

Table 7: Univariate analysis shows Berg Balance Scale and Chedoke-McMaster Stroke Assessment to be positively correlated with all dependent variables, with the exception of cadence/step length ratio.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Berg</th>
<th>CMSA Leg</th>
<th>CMSA Foot</th>
<th>MAS Gastrocnemius</th>
<th>MAS Soleus</th>
<th>MAS Knee</th>
<th>Age</th>
<th>Time Post-Stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred Gait Velocity</td>
<td>0.39**</td>
<td>0.34*</td>
<td>0.26*</td>
<td>-0.10</td>
<td>-0.22</td>
<td>-0.14</td>
<td>-0.09</td>
<td>0.26*</td>
</tr>
<tr>
<td>Maximum Gait Velocity</td>
<td>0.46**</td>
<td>0.37*</td>
<td>0.30*</td>
<td>-0.14</td>
<td>-0.22</td>
<td>-0.15</td>
<td>-0.13</td>
<td>0.27*</td>
</tr>
<tr>
<td>Cadence (Preferred)</td>
<td>0.34*</td>
<td>0.38*</td>
<td>0.30*</td>
<td>-0.11</td>
<td>-0.26*</td>
<td>-0.11</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Cadence (Maximum)</td>
<td>0.39**</td>
<td>0.39*</td>
<td>0.29*</td>
<td>-0.06</td>
<td>-0.17</td>
<td>-0.08</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>Step Length (Preferred)</td>
<td>0.38**</td>
<td>0.31*</td>
<td>0.25*</td>
<td>-0.08</td>
<td>-0.18</td>
<td>-0.16</td>
<td>-0.18</td>
<td>0.38**</td>
</tr>
<tr>
<td>Step Length (Maximum)</td>
<td>0.40**</td>
<td>0.26*</td>
<td>0.24*</td>
<td>-0.17</td>
<td>-0.21</td>
<td>-0.17</td>
<td>-0.23</td>
<td>0.34*</td>
</tr>
<tr>
<td>Ratio (Preferred)</td>
<td>-0.23</td>
<td>-0.05</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.09</td>
<td>0.31</td>
<td>-0.29*</td>
</tr>
<tr>
<td>Ratio (Maximum)</td>
<td>-0.06</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
<td>0.02</td>
<td>0.08</td>
<td>0.36</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

Multivariate analysis included a full model analysis featuring the 8-variables characterizing the individuals with stroke, with the dependant measures being velocity, step
length, cadence, and ratio. Overall, with all the variables kept, the full model was able to account for between 13-35% of the variance in the dependent variables (Table 8).

Stepwise regression analysis uncovered age and time post-stroke to be significant predictors of preferred ratio ($R^2=0.20; P = 0.0053$), with age being the only significant predictor of ratio at maximum gait velocity ($R^2=0.13; P = 0.0002$). The leg sub score of the CMSA was the only statistically significant predictor of cadence at both preferred ($R^2=0.14; P=0.0013$) and maximum ($R^2=0.16; P =0.0007$) velocity. Step length had the most variance accounted for by post-stroke impairment at both preferred and maximum gait velocity for all gait variables; the combined $R^2$ was 0.33 and 0.35, respectively. A significant positive relationship was found between step length and both functional balance and time post-stroke. Meanwhile, age and the soleus sub-score of the MAS (maximum gait velocity) were found to have a significant negative relationship with step length. A summary of significant variables and their relationship to all gait characteristics are reported in Table 8.

Table 8: Results of step-wise multivariate regression between independent variables (8 variables) and gait characteristics for stroke. Results are shown for analysis of preferred and maximum gait velocity. Direction of relationship, R-square, p-value, and combined R-square ($R^3$) are reported.
4.5 Discussion

The results of the current study do not support our hypothesis that there is a difference in the strategy used by individuals with stroke to increase gait velocity, in comparison to the healthy population. In addition, the difference between the strategies adopted at preferred and maximum gait velocity, as measured by the cadence-to-step length ratio, within the stroke population were also found to not be statistically significant. With respect to the relationship between individual characteristics and gait characteristics, there were important differences in the factors that were associated with step length, cadence and the ratio of cadence/step length. For example, functional balance presented to have a significant relationship with step length at both preferred and maximum velocity. Interestingly, age and time post-stroke (at preferred gait velocity) were the only statistically significant variables relating to the cadence-to-step length ratio, our categorical variable.

Previous literature has found the preferred gait velocity of individuals following stroke to be lower than that of healthy individuals (Turnbull et al., 1995). Our results are in agreement with this finding as the final achieved preferred gait velocity of individuals with stroke (0.85 m/s) was far below that of healthy individuals (1.19 m/s). In addition, the preferred gait velocity of our stroke group was within the upper range for average group scores that have been reported in individuals with stroke, approximately 0.45 m/s to 1.05 m/s (Knutsson & Richards, 1979; Olney et al., 1994). Forty-one percent of our participants had a maximum gait velocity slower than the average preferred velocity of healthy individuals. The average maximum gait velocity achieved by the individuals with stroke was still below some minimum velocity
requirements for community walking, which has been reported to be between 0.66 m/s (van de Port et al., 2008) and 1.32 m/s (Lerner-Frankiel et al., 1986).

The wide range of values at maximum when compared to preferred gait velocity, as well as the wide range of within-subject change scores, demonstrates that not all individuals with stroke have the same capacity or resources to increase gait velocity. This result is further emphasized by the distribution of the cadence-to-step length ratio between preferred and maximum gait velocity. This difference reveals the difficulty some individuals have at accessing and utilizing the functional resources necessary to increase gait velocity. Maximum gait velocity requires the body to go through a greater ROM, create increased levels of joint muscle torques to maintain joint stability, develop additional muscular power to propel the body forward. In order to achieve this, a high level of system coordination is required (Hsu et al., 2003). This level of system coordination may not be fully intact in individuals who have suffered a stroke.

Within this study, gait was explored both in terms of velocity as well as cadence and step length, in order to further uncover the cause of the slowed velocity found in individuals following stroke. The strategy, measured using the cadence-to-step length ratio, was used as a composite measure of the trade-off between cadence and velocity to achieve a specific velocity. Previous research has revealed that individuals with stroke rely on cadence more than step length at both preferred and maximum gait velocity versus healthy controls (Jonsdottir et al., 2009). With this in mind, it was hypothesized that independent of velocity, individuals with stroke would rely more on cadence than step length at both higher velocities and when compared to healthy individuals. Yet, the present study did not reveal a statistically significant difference in the mean ratio between the groups. In contrast, the within-subject change of
cadence was much higher and much more variable than that of step length, revealing the need for individual comparisons for future studies.

Though a statistically significant difference in the cadence-to-step length ratio was not observed between preferred and maximum gait velocity within the stroke group, the role of cadence for increasing gait velocity was evident. At preferred gait velocity the group had a notably smaller variance in cadence versus maximum gait velocity. The within-subject difference of cadence between preferred and maximum gait velocity, which was found within the current study to be statistically significant, has been reported consistently in the literature (Jonsdottir et al., 2009). In fact, many studies have speculated that this reliance on cadence could be the result of adaptations in the presence of physical limitations imposed by post-stroke impairment (Larish et al., 1988).

Step length, which was of major interest during the current study due to its possible limiting effect on maximum gait velocity in individuals with stroke, was predominantly influenced by three variables; age, time post-stroke, and functional balance. Commonly, functional balance is seen as a primary determinant of gait velocity within this population (Witte & Carlsson, 1997; Study 1) and this may be linked, in part, to the willingness and/or ability to increase step length. Functional balance requires the integration of numerous body systems including the neuromuscular (strength, coordination, co-contraction, etc.) and sensory (proprioceptive, visual, and vestibular) systems and is necessary for all functional activities (Yavuzer et al., 2006). The composite nature of the measure makes functional balance difficult to assess due to the inability to differentiate between the various components, and therefore,
difficult to rehabilitate. Focusing research on its fundamental components may help tease out the underlying mechanisms and give direction for clinical gait rehabilitation following stroke.

The main outcome variable, the cadence-to-step length ratio, was uniquely predicted by age and time post-stroke (at preferred gait velocity). Age is seen in the literature to have a negative relationship with gait velocity as well as step length in the healthy population (O'Brien et al., 1983), yet within individuals with stroke, this relationship is often overshadowed by the role of post-stroke impairment. Our study may demonstrate the role age plays in the ability to recover after stroke. Utilizing a higher range of impairment scores and comparing higher impairment with lower impairment, with respect to gait velocity, cadence, step length, and cadence/step length ratio, may reveal additional relationships within this population.

Although many of the impairment scores used in this study were found not to be associated with our dependent variables, within the full model, they still contributed by accounting for some additional variance. While the absence of association between impairment scores and the dependent variables could be attributable to the composite nature of some of the measures, their significance within the model reveals some level of relationship with each gait variable. In spite of this, the overall model for each of our dependent variables accounted for only 13-35% of the variance in these gait variables, leading one to believe there are still important measures which may better predict gait velocity after stroke. Additional research should be directed at comparing the ratio of individuals with stroke and healthy individuals walking at the same velocity in order to develop a better understanding of the categorization between groups. Assessing the pre-existing motor patterns which may be a cause of this cadence-to-step length ratio is also warranted. The use of lower functioning individuals could
also lend more perspective to the underlying control mechanisms of this cadence-to-step length ratio and the impairments influencing its composition. Once these relationships have been established, an intervention focused on the manipulation of this ratio to develop new motor pathways could aid in clinical rehabilitation. Due to the high functional level of stroke participants within this study, one should be careful in the generalization of these results in a heterogeneous population such as stroke.
5.0 General Discussion

The purpose of the present work was to investigate the factors associated with gait velocity after stroke. In order to test this, two studies were conducted. The first sought to determine the association between specific impairments and preferred and maximum gait velocity. It was discovered that functional balance control deficits were most predictive of decreases in both preferred and maximum gait velocity, as well as a decreased ability to increase gait velocity (difference between maximum and preferred). The second study attempted to characterize the strategy used by individuals to achieve a particular velocity through the calculation of cadence-to-step length ratio and comparing against age-matched controls. In addition, the study explored the relationship of post-stroke impairments to gait characteristics, including cadence/step length ratio. In contrast to our prediction, no statistically significant difference was found between individuals with stroke and healthy individuals. Overall, age was the single most important predictor of the cadence/step length relationship. Together, the results of these studies indicate that balance, and the impairments that affect balance are of vital importance to the recovery of walking within individuals who have experienced a stroke.

Of the variables that did relate to gait velocity, functional balance was most consistent, which is in agreement with previous research (Yavuzer et al., 2006). This decline in balance leads to increased falls risk (Nyberg & Gustafson, 1995), decreased balance confidence (Botner et al., 2005), and a slowed velocity (von Schroeder et al., 1995). This decline is the similar to that found as people age. It has been reported that the elderly population experiences an increase in number of falls (Rubenstein, 2006) and a decrease in gait velocity (Bohannon, 1997).
as a result of this decline in balance. Balance is necessary for all functional activities, including sitting, standing, and walking. Since balance requires the integration of numerous body systems (e.g. muscular, neural, proprioceptive, vestibular, and visual systems), impairments disturbing any one of these components of balance will impair one's ability to accomplish certain tasks.

Functional balance was also found to be essential for the regulation and maximization of gait velocity following stroke. More specifically, functional balance was related to step length, the component of velocity proposed to be the limiting factor in post-stroke gait velocity. Balance can cause difficulties with creating necessary joint-muscle torques, limiting one's ability to sustain single-support. It may also be the result of several post-stroke impairments, such as muscle weakness and sensory impairment (Schenkman et al., 1989). Therefore, gait rehabilitation which includes specific balance components would be better suited for those individuals with the specific goal of attaining independent walking within the community.

As a primary approach to better understand the factors associated with gait velocity after stroke, different multivariate models were used. And, while these models included impairments reported in the literature to be related to primary gait characteristics, the models also demonstrated a low capacity to predict our gait characteristics. This highlights the complexity of the factors that determine gait, including many variables that were not included in the present analysis (e.g. pre-existing motor pathways, specific ROM and strength scores, and psychological factors). While the impairment following stroke is of obvious importance, the pre-stroke status of individuals should also be taken into account. Motor learning is known to be determined on both genetic and environmental factors (Fox et al., 1996), and even with the neurological disturbance caused by stroke, residual motor pathways may still be present. From
previous research we know that not all lower limb strength or ROM scores are associated with
gait velocity (Bohannon, 1986). The use of a composite measure, such as the CMSA, which
would include input from all lower limb strength scores, may overshadow or understate the
importance of various muscle groups. Even if all motor control issues and strength/ROM scores
are accounted for, the willingness of the participant is still dependent on intrinsic motivation.
Further research should aim to narrow down these additional factors and try to account for the
psychological and neural components of gait.

The current work may emphasize use of an approach focussed more specifically on
individual characteristics given the heterogeneity. Certainly a focus on functional balance
training within the gait rehabilitation program is required as it is an important determinant for
increased gait velocity and therefore independent walking within the community. In
conjunction with this, the use of the ratio calculated within this study may provide an easily
quantifiable and comparable tool for determining, not only the relative contribution of cadence
and step length to achieve a particular velocity, but also a direction for therapeutic
interventions. From this thesis we have knowledge regarding the factors associated with both
cadence and step length. Therefore, knowing the relative contribution of cadence and step
length to gait velocity can remove redundancies within clinical rehabilitation by ensuring
rehabilitation is only focused on those impairments directly affecting gait function. Further
research is needed to determine the precise role this ratio could play in rehabilitation.

5.1 Limitations

There were limitations associated with the current study including: 1) the properties of
the BBS, which is found to be accurate with lower functioning individuals, but which may not be
sensitive enough for those who are high functioning and capable of walking independently; 2) the use of composite measures (BBS and CMSA) instead of specific strength, sensory, or range-of-motion measures may detract from the robustness of the results; 3) the criteria for inclusion and exclusion was too stringent for lower functioning individuals to participate, potentially missing important relationships between impairment and dependent variables and limiting generalizability to the wider stroke population; 4) comparison of ratios were not velocity matched or normalized; 5) generalizability due to recruitment and same participants for both studies; and 6) there are limits to the accuracy of gait velocity, step length, and cadence, as measured using the GAITRite® walkway.

The BBS was developed to assess balance in elderly, community-dwelling individuals. The scale consists of 14 items scored on a scale from 0-4 with a total possible score of 56. Although the scale has been reported to be valid and reliable in individuals with stroke (Berg et al., 1995), concerns have been raised over the potential for ceiling effects (Mao et al., 2002). Due to this ceiling effect, and the potential role it plays in more high-functioning participants, a more sensitive measure of functional balance may provide additional information upon which to compare participants.

Both the Berg Balance Scale and the Chedoke-McMaster Stroke Assessment can be categorized as composite measures of impairment. These measures do not measure specific aspects of post-stroke impairment. Decreased balance alone may be the result of several impairments directly resulting from stroke (e.g., muscle weakness and sensory impairment) (Schenkman & Butler, 1989). The CMSA, which measures motor impairment, also includes measures of muscle strength, ROM, and hypertonia (Miller et al., 2008). The CMSA, along with
the BBS, may overshadow individual impairments, and undermine the value of the analysis. Composite measures such as these are useful clinically for classification and tracking progress; yet specific measures may give more insight as to specific underlying impairment affecting post-stroke gait.

Our study necessitated individuals with the ability to walk independently, as an increase in gait velocity through independent walking was an outcome goal. This requirement led to the inclusion of primarily high functioning individuals with lower levels of impairment, measured using our impairment measures (BBS, CMSA, and MAS). This high level of functioning could also account for the high average preferred gait velocity of our study group, compared to previous studies. The possible inclusion of individuals who use gait aids may be necessary to better understand the role of impairment on gait velocity and expand the generalizability of results.

Within our second study, we calculated strategy using a novel cadence-to-step length ratio and compared this ratio between healthy individuals and individuals with stroke. This strategy was computed and compared as a group measure with no adjustment for attained velocity. The use of velocity-matched controls has been used before in previous research (Chen et al., 2005), yet your group did not allow for such adjustments. This recommendation for adjustment does not come without its own difficulties. Since the majority of individuals with stroke walk at a slower gait velocity than healthy individuals, the potential need for healthy individuals to walk at a gait velocity lower than what is considered comfortable for them may be necessary, potentially leading to changes in the gait pattern not normally present in self-selected walking. It is recommended that future research use this adjustment strategy with caution to better compare strategy between groups.
The Heart and Stroke Foundation Centre for Stroke Recovery longitudinal database recruits participants from four (4) hospitals (1 acute care, 3 rehabilitation). The hospitals utilized the populations within or surrounding their particular hospitals. This creates a sampling bias and may not be representative of the very heterogeneous population, and therefore not generalizable to those outside of the sampling area. Individuals within this study may also differ in their previous or current rehabilitation history. Individuals in the acute phase, due to the day-to-day variability in the ability of these individuals, may not have been tested to their highest ability. In the same way, individuals in the chronic phase have already undergone rehabilitation and may have even developed compensations for underlying impairments. There is additional variability in having different individuals collecting the data, as differing instructions and inter-rater variability within the clinical measures can also affect results. Now both studies utilized the same participants, so caution must be used in drawing firm conclusions and generalizing the findings of both studies to the entire stroke population.

The GAITRite® Walkway, while shown to be valid and reliable (Bilney et al., 2003), has certain limitations due to the spacing between sensors, sampling rate, and the assumptions used during the calculation of each variable measured. The spatial resolution, which is 0.5” (1.27cm), allows for some variance between steps both within the same trial, between trials, and between individuals. The default sampling rate is 80Hz, yet can range from 60-240Hz. The ability to alter this allows for more accuracy, especially as velocity increases. Since our population had a relatively low gait velocity, the default sampling rate was used. Finally, when the GAITRite® calculates velocity, the distance traveled is divided by the ambulation time. This is expressed in centimeters per second (cm/sec).
5.2 Future Directions

The findings from this study present an opportunity for additional research surrounding many areas: 1) continue to explore metrics of gait that may reveal personal and task specific differences such as the cadence-to-step length ratio including factors that may lead to the alteration of an individual’s strategy; 2) developing a minimal detectable change for independent walkers between preferred and maximum gait velocity; 3) a randomized control trial aimed at a combined intervention including gait training in conjunction with an impairment focussed rehabilitation regime based on the individuals limiting factors.

Firstly, although the current study did not find statistically significant differences in strategy between groups, the cadence-to-step length ratio still presents a potentially unique and important classification method. As stated within the limitations of our study, utilizing velocity-matched individuals and allowing for lower functioning individuals with stroke may unveil important differences between groups. Uncovering differences in motor patterns between the healthy and post-stroke population, as well as within the stroke population alone, could have important clinical implications for rehabilitation.

Secondly, research has developed a minimal detectable change for individuals through rehabilitation. This change is simply the minimum increase in gait velocity necessary to ensure inter-trial variability is not the source of the change. Research has not yet developed a minimum detectible change between preferred and maximum gait velocity. This information would give a reference point to better identify those individuals with severe difficulties in their capacity to increase gait velocity and in need of additional gait rehabilitation.
Finally, gait specific rehabilitation could assist in the achievement of higher gait velocities in individuals post-stroke. Identifying the specific impairment limiting each individual's gait velocity and combining this knowledge with current gait training protocols may allow individuals to have faster and more complete recovery following stroke. Research regarding the techniques for gait training, including over-speed training (Wada et al., 2010) and body support treadmill training (Moseley et al., 2005), have continued to progress. However, while these training protocols achieve positive effects, they often do not include impairment focused rehabilitation. Combining the two forms of rehabilitation, both with the same overall goal, could significantly increase the number of individuals walking independently within the community following stroke.

5.3 Conclusions

To our knowledge, this is the first work that has looked to determine the relationship between the strategy one uses (cadence-to-step length ratio) and compare this strategy between individuals with stroke and the healthy population. Previous research has shown individuals with stroke to walk slower, with higher cadence, and lower step length than healthy individuals at preferred and maximum gait velocity. Clearly gait velocity is not the only determinant of community walking, yet its importance cannot be overstated. Therefore, a focus on additional barriers to community walking, along with gait velocity will lead to the most fruitful interventions. Further investigation is necessary to determine the usefulness of this ratio to inform clinical practice for the alteration of post-stroke gait patterns.
6.0 References


