A Novel Approach to Ambulatory Monitoring: An Investigation into Everyday Walking Activity in Patients with Sub-Acute Stroke

by

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Abstract

Walking is an essential task important to recovery after stroke. However, there is a limited understanding regarding the characteristics of walking in in-patients with stroke. The objectives of this thesis were to: 1) develop an instrument capable of acquiring temporal characteristics of everyday walking; 2) investigate the quantity and control of everyday walking; and 3) profile the task-specific link between walking and cardiorespiratory response. In study 1 we developed and validated a wireless monitoring system (ABLE system). Study 2 revealed low quantities of everyday walking (\( \bar{x} 4816 \text{ steps}; \text{SD} 3247 \)) characterized by short bout durations (\( \bar{x} 59.8 \text{s}; \text{SD} 23.4 \)) and asymmetric walking. In study 3 we observed a modest task-related response in HR (19.4% HRR); however, the intensity and duration of everyday walking did not approach the guidelines for aerobic benefit. Monitoring in-patient walking can help guide clinical decision making in developing methods to maximize recovery after stroke.
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Abbreviations

ABLE: Accelerometry for the Bilateral Lower Extremities
ACSM: American College of Sports Medicine
ADL: Activities of daily living
ANOVA: Analysis of variance
BBS: Berg Balance Scale
CI: Confidence interval
CMSA: Chedoke-McMaster Stroke Assessment
DLS: Double-limb support
FC: Foot contact
FO: Foot off
HR: Heart rate
HRR: Heart rate reserve
MCA: Middle cerebral artery
PDA: Personal digital assistant
SD: Standard deviation
SLA: Stereolithography
SMWT: Six Minute Walk Test
SPC: Single point cane
TT: Treadmill training
VOF: Vertical-orientation factor
1.0 Introduction

1.1 Overview

Stroke is one of the leading causes of adult disability in Canada effecting more than 50,000 Canadians each year (Heart and Stroke Foundation of Ontario, 2002). In addition to serious neurological deficits, up to 40% of individuals with stroke suffer from profound physical de-conditioning, which leads to a moderate to severe level of physical disability (Heart and Stroke Foundation of Ontario, 2002). More importantly, significant impairments to sensorimotor control and/or cardiorespiratory fitness can contribute to disability and influence the quantity of inactivity leading to an increased risk of subsequent stroke.

To counter such post-stroke decline, physical rehabilitation in the acute stage (first 14 days) of stroke to the sub-acute (up to the first 3 months) and continued through the chronic stage (> three months) is recommended to help patients retrain lost motor functions and regain their capacity to perform essential activities of daily living (ADL) (Stergiou, 2004). In rehabilitation practice, the use of task-specific activities is a commonly used approach to counter post-stroke decline (Ivey, Hafer-Macko, & Macko, 2008; Macko et al., 2001; Macko et al., 2005). Therefore, the current focus is directed towards whole body movements like walking and biking (e.g. cycle ergonimeter) that may influence mobility and/or fitness capacity. Furthermore, whole body movements contribute to reducing sensorimotor dysfunction and cardiovascular de-conditioning.

While there are many types of task-specific activities that are important to post-stroke recovery, our particular interest is in post-stroke gait, or walking. The focus on walking is based on the view that regaining walking competency is one of the most commonly cited goals for patients entering rehabilitation (Bohannon, Andrew, & Smith, 1988). Furthermore, improved walking function and capacity is closely coupled with the ability of patients to successfully perform ADL. More globally, walking is a task which may be performed independently in different places without the use of exercise equipment. When walking is performed at the recommended intensity and duration for aerobic exercise (Franklin, Whaley, & Howley, 2000; Gordon et al., 2004), it can help improve both sensorimotor control and cardiovascular fitness (Macko et al., 2001; Macko, Ivey, & Forrester, 2005). Therefore, there are many reasons why walking activity is beneficial to recovery after stroke.
Given the positive influence walking activity has on post-stroke recovery, the following studies attempt to investigate the quantity (e.g. bout duration and cumulative quantity) and control (e.g. gait symmetry) of walking as well as the cardiorespiratory link to everyday walking in patients with sub-acute stroke during their stay in a rehabilitation facility. Currently, we know a large portion of physical rehabilitation is devoted to gait retraining to improve neuromuscular control of walking and overall walking capacity (Latham et al., 2005). However, beyond the traditional clinical/therapeutic setting (e.g. physical/occupational therapy) the quantity of patient activity, including the quantity of walking, is considerably less (Lincoln, Willis, Philips, Juby, & Berman, 1996). It is our view that during these periods of inactivity there is a missed opportunity to increase the quantity of walking and improve the status of walking control. By developing methods to monitor everyday walking, it is possible to provide an objective examination regarding the characteristics and control of everyday walking and associated cardiovascular loads during everyday walking. In addition, monitoring everyday walking will help uncover potential factors that influence the characteristics of overall walking (i.e. intensity, frequency and duration) in patients residing in a rehabilitation facility. This can be used to promote additional bouts everyday walking, not only during therapy but during periods of unstructured time, which can have the potential to positively influence post-stroke recovery.

Ambulatory monitoring research in individuals post-stroke has demonstrated that the total quantity of everyday walking, with respect to the total number of steps taken, is low (Michael & Macko, 2007; Shaughnessy, Michael, Sorkin, & Macko, 2005; Tudor-Locke & Bassett, 2004) with the lowest cumulative amounts of walking occurring during the acute stage of stroke (Bernhardt, Chan, Nicola, & Collier, 2007). The overall quantity of walking has been shown to increase as patients transition to the sub-acute stage of stroke; however, as patients reintegrate back into the community the quantity of walking regresses in many patients (Kelly, Kilbreath, Davis, Zeman, & Raymond, 2003; Michael & Macko, 2007). Compared to healthy aged-matched individuals, the overall quantity of walking observed in chronic patients in the community is low (Michael, Allen, & Macko, 2005; Tudor-Locke & Bassett, 2004). The decrease in walking quantity by individuals with stroke in the community is likely influenced by a drop in the frequency of therapy received and by environment factors associated with community living.
‘Ambulatory activity monitors’ are instruments used to quantify walking behavior (Mudge, Stott, & Walt, 2007; Rand, Eng, Tang, Jeng, & Hung, 2009; Schutz, Weinsier, Terrier, & Durrer, 2002; Shepherd, Toloza, McClung, & Schmalzried, 1999). These instruments report walking characteristics primarily in the form of total step count and/or total walking time. While these instruments are able to characterize the overall quantity of post-stroke walking (e.g. total steps and bout time) they lack specificity to measure more detailed characteristics of walking. For example, these devices do not typically provide details of the time-of-day and duration of individual bouts of walking and more importantly the temporal characteristics of each step. Such information can be used to report indices such as gait symmetry, which provide a reflection of the control of walking. We consider the use of such temporal gait information as important and complementary information that may help guide clinicians and patients to maximize recovery during an in-patient stay. As a result, a key objective for the present work is to develop and validate a wireless measurement tool capable of providing detailed information about daily walking in patients with stroke.

1.2 Profile of Stroke Recovery
In one of the first studies to have profiled the course of stroke recovery, the progression of recovery was described as a predictable step-wise sequence of functional milestones in which patients could plateau at any time (Twitchell, 1951). The advent of several clinical measures that better characterize patient behavior has allowed for a more detailed, objective examination of patient recovery. Within the first three months after the onset of stroke patients generally experience the greatest extent of behavioral/motor recovery through spontaneous recovery (Richards & Olney, 1996). But, due to typical heterogeneity of neurological and behavioral deficits following stroke, the actual timeline for recovery is unique to each individual as it is dependent on a number of factors, such as the severity of initial deficits and state of pre-morbid functioning. The former, the initial extent of paresis and disability, is regarded as a primary determinant for the extent of eventual recovery (Hendricks, van Limbeek, Geurts, & Zwarts, 2002; Jorgensen et al., 1995). Thus, in the months following stroke, patients suffering from mild deficits are more likely to have a better prognosis and experience an earlier recovery than those suffering from more severe deficits (Hendricks et al., 2002).
For the majority of patients, restitution of function following recovery is incomplete and as a result patients can be left with significant levels of impairment and/or disability. Prospective studies demonstrate a plateau in motor recovery around the six month mark after stroke in 95% of patients receiving standard therapeutic care, with some studies reporting improvements to functional outcomes up to one year after stroke onset and in one case five years post-stroke (Richards & Olney, 1996). In addition to the factors mentioned (e.g. severity of initial deficits and level of pre-stroke activity), the progression of recovery is also dependent on both the amount of overall physical activity and the specific types of activity engaged in by patients. Before exploring methods to promote the quantity and types of specific post-stroke activity, it is essential to first understand the characteristics of physical activity after stroke.

1.3 Promoting Post-Stroke Activity

1.3.1 Physical Inactivity and Role of Exercise

The reduction in physical activity is a common and an alarming occurrence at all stages of stroke recovery (Bernhardt et al., 2007; Haeuber, Shaughnessy, Forrester, Coleman, & Macko, 2004; Manns & Baldwin, 2009; Michael et al., 2005). For example, patients within the first 14 days after onset of stroke receive less than an hour of structured therapy (e.g. physical/occupational) throughout the day (Bernhardt, Dewey, Thrift, & Donnan, 2004). At the sub-acute stage of stroke, overall quantities of physical activity are greater compared to the acute stage; however, the overall quantity of physical activity is still considered to be quite low relative to age-matched healthy individuals (Michael et al., 2005). Consequently, low levels of whole body exercises can lead to greater activity/exercise intolerance in patients (Mol & Baker, 1991). The concern with lower physical activity participation is that physical inactivity can contribute to a negative cyclical pattern of neuromuscular dysfunction and aerobic deconditioning. Examples of further decline include learned non-use of the paretic limbs, muscle atrophy, and most importantly increased risk of subsequent cardiovascular disease (Ivey, Hafer-Macko, & Macko, 2006). Consequences of physical inactivity post-stroke are significant and therefore a major focus of rehabilitation should be on increasing patient activity.

There is clear support that increasing the quantity of overall physical activity can counter the significant deconditioning associated with chronic disability (Gordon et al., 2004). With respect to overall activity, there is an emphasis on combining models of aerobic training and motor
learning to promote the use of task-specific training (Tang, Sibley, Brooks, Thomas, & McIlroy, 2004). Task-specific exercise therapy is an effective strategy that contributes towards improving the overall health status of patients by supporting positive neuromuscular and cardiovascular adaptations to counter the effects of inactivity (Macko et al., 2005). Moreover, task-specific activities are beneficial to overall health because this approach simultaneously mobilizes and adapts multiple physiological systems such as the central nervous, cardiorespiratory and musculoskeletal systems (Ivey et al., 2008).

In the present thesis, there is a particular interest in walking as a task-specific activity to promote recovery after stroke. Based on the ability to address both impairments to sensorimotor control and cardiorespiratory fitness, the advantages of walking to address both these factors has been demonstrated by task-specific treadmill training (TT) paradigms in the rehabilitation setting (Macko et al., 2001; Macko et al., 2005). The use of TT or similar gait related paradigms exploits principles of motor skill learning through relevant task repetition training (Macko et al., 2005; Plautz, Milliken, & Nudo, 2000) and inherent reflexive gait patterning (Ivey et al., 2006). In terms of neuromuscular adoptions, studies using TT have shown to induce immediate changes to muscle activation patterns in the quadriceps muscle (Harris-Love, Macko, Whitall, & Forrester, 2004). When combined with an aerobic exercise program, TT improves peak exercise and walking capacity and lowers the energy cost of hemiparetic gait (Macko, Ivey, & Forrester, 2005).

Promoting walking as a strategy for stroke recovery is based on experimental evidence (mentioned above) and more simply based on the view that walking activity is a task which can be independently performed by some stroke survivors, without any equipment and at anytime of the day. Given the contributions of walking to the progression of recovery following stroke, it is important to encourage patients with stroke to become more active and increase their quantity and control of walking when these individuals have the capacity to walk independently and safely.
1.4 Post-Stroke Gait

1.4.1 Recovery and Characteristics of Post-Stroke Gait

Like overall motor recovery, walking recovery is also primarily observed within the initial 3 months following stroke, with improvements observed up to and beyond the 6 month mark (Duncan et al., 2003; Jorgensen et al., 1995). Results of ambulatory recovery from the Copenhagen study demonstrated that from 935 patients residing in an in-patient hospital, restoration of walking function occurred in 95% of patients within the first 11 weeks after stroke (Jorgensen et al., 1995). Again the extent of walking recovery was dependent on the level of initial paresis and the degree of walking function initially lost. It was suggested that prognosis of walking functioning in patients with mild leg paresis can be accurately made within the first three weeks and further ambulatory recovery should not be expected beyond 9 weeks (Jorgensen et al., 1995). While there are likely concerns about such definitive and potentially conflicting post-stroke recovery timelines, what is most relevant to the current thesis is the early window of time following stroke that has the potential to significantly influence recovery of walking. This rationale serves as the basis for our focus on in-patient (sub-acute) recovery.

Following stroke there are clear differences in the characteristics of walking between post-stroke and healthy age-matched individuals. One of hallmarks of post-stroke walking is the decrease in gait velocity (Bohannon et al., 1988; Goldie, Matyas, & Evans, 2001; Lamontagne, Stephenson, & Fung, 2007; Richards & Olney, 1996). The decrease is associated with shorter stride lengths accompanied by longer gait cycle durations. Depending on the severity of stroke, preferred walking velocity ranges from 0.18 to 1.03 m/s (Hsu, Tang, & Jan, 2003; Patterson et al., 2008) in stroke compared to healthy older adults who walk an average preferred velocity of 1.4 m/s (Hsu et al., 2003). Other alterations to gait, which are just as important but perhaps less evident, include 1) changes to gait patterning (i.e. gait asymmetry) (Goldie et al., 2001); 2) increase energy expenditure (Zamparo, 1995); and 3) decline in functional/performance measures (Macko, Ivey, & Forrester, 2005; Sibley, Tang, Brooks, & McIlroy, 2008).

1.4.2 Spatiotemporal Characteristics of Gait Following Stroke

To better understand the temporal characteristics of walking, it is important to address the different phases of the gait cycle and how they change after stroke. Overall alternating movements of the lower extremities can be broken down into specific phases of gait that are
defined by the timing of foot-contact (FC) and foot-off events (FO) for each foot. A gait cycle is defined as the series of activities that occur between FC of one limb and the subsequent FC of that same limb. This period of time can be divided into three overlapping phases: stance, swing and double support. The first, stance (or support) phase, begins with the FC of one foot and ends when the FO of that same foot leaves the ground; this occurs for approximately 60% of the entire gait cycle. The second phase, swing (or unsupported) phase, occurs for approximately 40% of the entire gait cycle and begins with FO from one limb and ends with FC from the same limb. Together these two phases make up the entire gait cycle. Lastly, to provide stability during the forward progression of locomotion, periods of stance phase from both limbs overlap each other for 15-20% of the gait cycle to provide the 3rd phases called double limb support phase (DLS).

Following stroke, sensorimotor impairments to the lower limbs are found to be predominantly unilateral, contralateral to the lesioned hemisphere. Compared to healthy individuals, patient with stroke typically demonstrate a decrease in single limb stance time in the paretic limb (Balasubramanian, Neptune, & Kautz, 2009). This characteristic is more distinct in those who have difficulty maintaining balance or bearing weight on the paretic limb (Balasubramanian et al., 2009). Conversely, the un-paretic foot experiences an increase in single-limb stance time to help advance the paretic foot during locomotion and reduced weight bearing responsibilities on the paretic (Goldie et al., 2001). In addition to these changes, there are also changes to the initial stages of the DLS in the paretic limb. As DLS begins for the affected limb (i.e. the paretic limb is lead limb about to accept weight), Goldie et al. has reported an increase in DLS time, which demonstrates the inability of patients to transfer weight on their paretic limb. Collectively, these characteristics contribute to decreased walking velocity as the duration of a gait cycle is inversely proportional to cadence, a proxy measure to velocity. Importantly, these changes in control reflected in spatiotemporal characteristics are also reflected by the degree of symmetry between the two limbs.

1.4.3 Gait Symmetry

Of specific interest to the current study is the spatiotemporal property of gait described by gait symmetry, which is expressed as a ratio between the paretic limb and non-paretic limb for a given quantitative characteristic of gait. Indices of gait symmetry evaluate potential control problems manifested within the different phases of gait (Olney, 1993; Patterson et al., 2008) and
provide an alternative approach to conventional measures (i.e. gait velocity) when determining the extent of gait-specific impairments. Symmetry can be viewed as a gait-specific impairment because it reveals an altered pattern of movement (i.e. inter-limb coupling) during locomotion. Gait symmetry can be expressed as a spatial measure (e.g. step/stride length symmetry) and it can also be reported as a temporal measure (e.g. stance, swing, step, and stride time). The focus in this thesis will be just on measures of temporal symmetry, as measures of spatial symmetry may not be as prevalent in the sub-acute and chronic population (Patterson et al., 2008).

Temporal symmetry for normative gait is found to have a ratio between 0.9 and 1.1 (Patterson et al., 2008); however, unilateral lower limb impairments following stroke prevent patients from achieving symmetric gait and consequently lead to larger deviations from normative values. Symmetry values in excess of 1.1 or below 0.9 point toward asymmetric gait. Post-stroke gait can be characterized by much greater asymmetry values both at the sub-acute stage and in the community (Patterson et al., 2008). 55.5% of chronic stroke survivors in the community, classified as independent ambulators, still have persistent temporal asymmetries (Patterson et al., 2008). Although many patients continue to exhibit moderate to severe gait asymmetries while walking at their ‘optimal’ walking speed (Balasubramanian et al., 2009), the potential consequences of persisting gait asymmetries makes it an important index of impairment to address.

The presence of asymmetric gait is associated with an elevated energy expenditure which is further inflated as velocity of walking decreases (Zamparo, 1995), a common characteristic of asymmetric gait (Michael et al., 2005). Early rehabilitation of gait symmetry may enable walking to be become more efficient and potentially faster leading to improved overall ambulatory capacity (Michael et al., 2005). Gait asymmetry is a concern because over time moderate to severe asymmetries have the potential to lead to musculoskeletal pathologies in the unaffected limb. For example, a temporal gait asymmetry will lead to repetitive abnormal loading (i.e. increase in ground reaction force) in the unaffected limb. Longitudinal studies in amputee patient populations demonstrate that this form of loading can lead to joint degeneration problems (Nolan et al., 2003). The potential consequence of persistent gait asymmetries on walking function provides support for it to be addressed early on in therapy.
Currently, the measurement of gait symmetry over an extended period of time is limited because of the inability of measurement instruments to portably collect FO and FC. Within day, longitudinal evaluations of symmetry provide a more representative profile of gait asymmetry severity as opposed to clinical or laboratory measurements, which are done under supervision. The mere presence of a clinician or researcher during assessment may lead to momentary periods of walking at a greater level of control (e.g. patient functioning on their ‘best-behavior’). Therefore, longitudinal evaluations of gait symmetry may yield a more realistic measure of a patient’s walking competency compared to a laboratory assessment.

1.4.4 Gait Variability
Variability in spatiotemporal measures of gait has also been used to infer the status of walking control after stroke. Increased variability has been associated with gait abnormalities found in older adults (Balasubramanian et al., 2009; Brach, Studenski, Perera, VanSwearingen, & Newman, 2008; Hausdorff, Rios, & Edelberg, 2001), fallers, those with neurological disease and while simultaneously performing cognitive tasks (Plummer-D'Amato et al., 2008). Patients with stroke also demonstrate increases in measures of gait variability, such as step length, swing, preswing and stride time, when compared to healthy age-matched individuals. Between limbs, affected limb swing time variability is larger than the unaffected limb (Balasubramanian et al., 2009). The degree to which these deviate from normative value is primarily dependent on the level of impairment and dynamic stability control.

1.5 Approaches to Measure Spatiotemporal Characteristics of Gait
The first step in amending rehabilitation practice to improve the prognosis of recovery is recognizing the need to increase the quantity and even the control of task-specific activity, such as walking, following stroke. Often overlooked is that there is potential for additional benefits from activities that can be carried out by patients throughout day, particularly during periods of unsupervised, unstructured time. To better guide activity prescription there needs to be an objective evaluation of walking outside the structured clinical setting.

Early measurement methods to assess daily walking began with the use of a pedometer (Corder, Brage, & Ekelund, 2007), a miniature device worn at the hip used to determine periods of walking by detecting pelvic oscillations in the sagittal plane. However, as noted, pedometers are
limited in use due to a lack of outcome measures provided (e.g. symmetry, frequency and duration) and placement of the monitor at the hip, which can lead to reduced sensitivity during slow walking (Corder et al., 2007). Most importantly, pedometers have shown to have less accurate and reliable evaluations of cadence/stride counts in healthy individuals (Shepherd et al., 1999) and patients with stroke (Haeuber et al., 2004; Shaughnessy et al., 2005) when compared to more advanced microprocessor-based accelerometer systems.

Studies using accelerometer based systems over the past decade have provided a more detailed account of overall walking in various patient settings (Haeuber et al., 2004; Manns & Baldwin, 2009; Michael et al., 2005; Moore, MacDougall, & Ondo, 2008). For example, this approach to patient activity monitoring has been adopted in the field of public health, where 10,000 step/day has been recommended to achieve an adequate daily dose of physical activity (Tudor-Locke & Bassett, 2004). More importantly, these studies have provided valuable insight into the relationship between the quantity of overall walking and measures of motor recovery, cardiopulmonary fitness (Kelly et al., 2003; Michael et al., 2005), balance (Michael et al., 2005), and functional walking tasks (Mudge & Stott, 2009). The majority of accelerometer-based systems are uniaxial, identifying motion in the sagittal plane. However, the advantage with accelerometer systems compared to pedometers is that they are usually placed on the lower limb, unilaterally, making it more sensitive to ground impact forces of gait, even during slow walking. Furthermore, by providing step count in predetermined epochs they are also able to report a proxy measure of walking intensity and bout duration. Yet, accelerometer-based ambulatory activity monitors primarily report walking in units of activity counts and/or steps/strides per day. Also, even though each patient tested with a monitor is bio-calibrated for an acceleration threshold (Shepherd et al., 1999), it may be very easy to breach that threshold during non-ambulatory movements (Corder et al., 2007). The most important disadvantage of these monitors is that current devices are not placed bilaterally at the ankle and so walking outcomes do not reflect any interactions between the lower limbs. Therefore, depending on the measures required, existing monitoring systems are adequate for overall activity, but are not capable of acquiring important temporal, bilateral information from walking.

For ambulatory monitoring instruments to be even more relevant to therapeutic practice, additional temporal, bilateral information regarding each footfall during the course of an
inpatient day is required to obtain important measures of each foot fall, step time and symmetry. The availability of such outcome measures may be useful in better guiding therapeutic intervention during rehabilitation.

1.6 Overall Objective:
1) To develop a novel wireless instrument capable of acquiring detailed temporal characteristics of everyday walking and investigate the feasibility of such a system in patients with stroke.

2) Investigate measures of quantity (total steps, bout duration) and control (temporal gait measures) of everyday walking among sub-acute stroke patients within an in-patient rehabilitation hospital.

3) Investigate the link between cardiovascular responses and bouts of everyday walking to determine if sub-acute stroke in-patients meet the recommended intensities for aerobic benefits during everyday walking.
2.0 Experiment 1: Development and Feasibility of Accelerometry for the Bilateral Lower Extremities (The ABLE system)

2.1 Introduction
A variety of methodological approaches are used to quantify the characteristics of human gait with each method related to the type of measurement needed. Of specific interest to the current study are the temporal measures of gait, specifically, the measurement of both foot contact (FC) and foot off (FO) times from which many temporal measures of gait are calculated (e.g. cadence, stance, swing and double support times and symmetry). The interest in these temporal measures is led by its ability to help quantify the total amount of walking and reveal atypical gait patterns such as gait asymmetries. The latter is particularly important as it identifies impairments to sensorimotor and balance control. For these reasons, the focus of the present study is on the temporal characteristics of gait.

Another important issue relevant to the present study is the duration of gait data collection. Conventional gait assessments during inpatient rehab are focused on short bouts of walking, however we advocate for a complementary approach that examines temporal characteristics of walking over much longer intervals to capture details of ‘everyday’ walking. While clinical measures provide details of the control of walking there is concern that such a brief snapshot may not reveal the true characteristics of hemiparetic gait during ‘everyday’ activities. ‘Everyday walking’ is defined as any walking engaged in by patients through their in-patient day, including periods of structured therapy (e.g. physiotherapy) and unsupervised time. Potential differences in temporal measures between standard and ‘everyday’ assessments may be due to the fact that patients may be on their ‘best behavior’ when being clinically assessed and/or other factors related to ‘everyday’ walking (e.g. fatigue, dual tasking and obstacle avoidance). Therefore, combining the ability to monitor gait characteristics events over extended periods of time can provide important details regarding the pattern (i.e. frequency and duration) and control of walking. In short, we view it as potentially valuable to clinicians to capture the details of walking, as represented by temporal measures such as FC and FO, both in and outside of clinical/lab setting.

The measurement of temporal gait characteristics in clinical/lab settings often requires the use of wired/immobile data acquisition systems (e.g. use of foot-switches, pressure mats). While there a
number of portable wearable devices to capture ambulatory activity, there are no existing commercial or published instruments that have the capacity to provide detailed information of each FO and FC time over extend periods of time outside the clinic/lab setting and that are free of disrupting instrument wires. Existing ambulatory monitoring systems primarily report walking data using measures of step count (Shaughnessy, Michael, Sorkin, & Macko, 2005; Shepherd, Toloza, McClung, & Schmalzried, 1999) and thus are limited in providing temporally relevant information such as the durations of individual walks, time of day they occurred and more importantly the details of individual foot-falls.

In an attempt to address this gap in methodology, the purpose of the present investigation was to develop a portable, wireless measurement tool called the Accelerometry for the Bilateral Lower Extremities (ABLE) system that would be capable of measuring FC and FO from each limb while walking within and outside the clinic/lab setting. To address this overall purpose the study was divided into two parts: 1) develop and 2) validate an ambulatory system to measure FC/FO times. The specific objectives for part 1, the development phase were to: 1) design and develop appropriate instrument hardware for a wireless ambulatory monitoring system; 2) develop an algorithm (e.g. software) with the capacity to precisely indentify periods of FC and FO during walking activity and 3) determine the feasibility of the ABLE system in patients with sub-acute stroke. For part 2, the specific objective was to validate the accuracy of the ABLE system in indentify FO and FC gait events compared to a gold standard (footswitches). In the present study, the reference to validity of the ABLE system refers to predictive validity of the ABLE system to identify the temporal characteristics of FO and FC as determined by the footswitches.

2.2 Methods

Part 1: Development of ABLE system

**Hardware Development & Feasibility of the ABLE System:** To support the development of the ABLE system, both the hardware development and patient feasibility objectives were addressed concurrently.

The ABLE system consisted of three pieces of equipment; two accelerometer ankle units and a Hewlett-Packard hx2410 personal assistant device (PDA) data logger. The inclusion of a data logger was necessary based on the need to collect and store information from both limbs and to
synchronize data collection from both accelerometers. The data logger was loaded with custom Labview software which was responsible for connection and data acquisition from each of the accelerometer ankle unit. Also, the data logger was fitted with an extended battery to prolong the duration of data collection. Each accelerometer ankle unit contained a Freescale MMA7260Q tri-axial accelerometer (Sparkfun Electronics, Boulder, CO) and a 3.7V battery supply (Figure 2.1). This specific accelerometer board was chosen because it was a cost-effective accelerometer that contained a Bluetooth module for wireless communication. Communication between the accelerometer ankle units and the data logger was carried out via class 1 Bluetooth. To house both the accelerometer board and battery, the casing for each accelerometer unit was custom built using stereolithography (SLA) material. SLA was chosen because it was a durable and lightweight material that could be molded into a specific form required for the ABLE system.

Each accelerometer unit (with the battery) weighed 46 grams. The dimensions of each unit were 4.4cm x 1.9cm x 6.3cm. The ABLE system was capable of collecting data for up to 8-9 hours before both the accelerometer ankle units and data logger (with extended battery) had to be recharged. Therefore the length of data collection was limited by the power supply to the ABLE system.

Accelerometers were placed on the lateral malleolus due to its proximity to the foot. This provided an increased sensitivity to temporal walking events such as FO and FC during walking compared to accelerometers positioned at the hip or thigh. Also, when placed at the ankles, the accelerometers can provide minimal interference to everyday activities (e.g. sleeping, sitting).

Selecting an appropriate material to fasten the accelerometers around an ankle was an important step to ensure a tight fit to the limb (to reduce artifact motion) and to reduce possible skin irritation and compression. After consultations with occupational/physical therapists, a cotton-foam material (Fabrifoam, Exton, PA) was chosen to affix the ABLE system to patients. The material contained a cotton exterior with a rubber/foam inner lining which made it difficult to slide on surfaces. Each ankle-strap had a sewn-in pouch to securely hold each accelerometer unit. Velcro tabs were used to fasten the entire ankle-strap around the ankle (Figure 2.2). The data logger was placed in a fitted polyester pouch, which was then hung from a polyester belt that was
fastened around the waist. The pouch was able to change positions and swing around wait as needed.

To determine if the ankle-strap provided a snug fit and did not cause skin irritation, the ankle-straps along with the accelerometers were first tested on 5 healthy individuals (mean age ± SD 26.9 years ± 4.6) and then on 5 patients with sub-acute stroke (Table 2.1) for approximately 8 continuous hours during the course of an inpatient day. Individuals and patients tested were monitored every 2 hours throughout the collection period to ensure there were no signs of skin irritation/compression. If there was any indication of skin irritation or discomfort, the ABLE system was removed from the subject. At the end of data collection, subjects were interviewed to provide details about their experiences while wearing the system.

Software developments to extract FC and FO

*Collection*: Using Labview, a customized data collection program was developed to acquire and transmit data from the two accelerometers to the PDA. Data sent to the PDA from both the right and left accelerometer include: the X, Y, and Z value of raw acceleration, and a counter indicating the data point number. At the beginning, end and five minute interval within a data set a timestamp (e.g. hour: minute: second: millisecond) was added using the internal clock of the PDA. Accelerometer data was collected at 50Hz, which has been found to be an adequate sampling frequency for gait activity (Jeleń, Wit, Dudziński, & Nolan, 2008; Stergiou, 2004). Higher frequencies (e.g. 100/200Hz) would be required for more dynamic gait movements, such as running (Merriman & Turner, 2002; Stergiou, 2004). Although the sampling rate was set to 50 Hz, the true sampling rate at which data was sent to the PDA varied (± 1, 2 Hz) throughout the collection period and so timestamps were used to resample data during post-processing to 50 Hz (see step 1 of Analysis).

To feature extract FC and FO events, data from both accelerometer ankle units were transformed through a serious of steps demonstrated in Figure 2.3. FC and FO indentified from footswitches (B&L Engineering, Santa Ana, CA) were used as a temporal reference point to identify FO and FC. After data were collected, all analyses were conducted ‘offline’ on a separate personal computer.
**Analysis - Step 1 - Resampling & Filtering:** Using MatLab, data from both the left and right accelerometer were first merged together to create a single data set. Data were screened for potential dropped samples; if any were present, data would then be interpolated. Dropped samples rarely occurred (<10 samples per entire collection period) and were most commonly associated with Bluetooth disconnection between the accelerometers and the PDA. Synchronization of data between the two accelerometers was conducted by matching timestamps found at the beginning of each data set from each accelerometer. If sections within the data set where data from only one accelerometer was found, the entire data set was truncated to the length that contained data from both accelerometers. It was observed that at rest, the accelerometers experienced a 1g acceleration pointing down due to the effects of gravity. To separate the acceleration components of gravity and bodily motion (inertial acceleration), a 0.25 Hz high pass filter was used to subtract the gravitational component (Karantonis, Narayanan, Mathie, Lovell, & Celler, 2006).

**Step 2 – Initial Behavior Classification:** Sections of data were then classified into one of three categories, active-upright, active-non-upright or inactive. Using the equation shown below, this was determined by subtracting the ratio of acceleration amplitude in the X and Z planes to the total acceleration amplitude (X, Y, and Z plane) from 1.

\[
\text{Vertical Orientation Factor (VOF)} = 1 - \sqrt{X^2 + Z^2} / \sqrt{X^2 + Y^2 + Z^2}
\]

For sections of continuous activity an average VOF greater than 0.5 indicated that the orientation of the lower limb was upright. Active-upright are represented by activities such as walking and active-non-upright activities can be represented by use of a recombinant bike or movement while lying down. Periods of inactivity were defined as periods of time were the amplitude was less than 0.14g. This threshold was determined by examining peak acceleration values in the X and Y axes during rest.

**Step 3 – Walking, FO & FC Detection:** Only sections of data identified as active-upright were used in subsequent analysis. First, data were screened to determine if periods of data labeled ‘active-upright’ were periods of walking. For data to be classified as walking the data must have met the following criteria: 1) reciprocal limb motion; 2) 4 consecutive, alternating steps within
the desired cadence range (e.g. 50 – 150 steps/min); and 3) pauses in walking shorter than 5s. Reciprocal steps were identified by comparing the timing and order of large negativities (negative acceleration) in the Y-axis, which represented peak swing acceleration down and forward, between the left and right foot (Figure 2.4). These negativities also were used to determine the number of steps taken. In the final step, once periods of walking were identified, data were low-passed filtered at 10Hz to prepare data for FO/FC detection using a separate algorithm (Karantonis et al., 2006).

To help determine when FO and FC occur within a walking acceleration waveform, insole footswitches were concurrently used while the 5 healthy subjects walked down a 15 m walkway for three trials at slow, preferred and fast walking speeds. Acceleration profiles from each walk were superimposed with each other to produce an averaged waveform from which rules for FO and FC were developed (Figure 2.5).

FO and FC were identified from the acceleration signals by first determining FO. During the gait cycle, prior to FO, the heel is lifted off the ground raising the ankle in the vertical direction. This motion created positive peak acceleration in the acceleration profile before the ankle began to swing down and forward creating a negative peak in acceleration. To identify FO, the algorithm first identified the lowest point within a local negativity in the Y-axis (Figure 2.4). Once found, the algorithm then moved backwards in the data until the baseline was reached (i.e. acceleration output found during stance-phase on the Y-axis). The number of data points between the lowest point in the negativity and the initial baseline-crossing was multiplied by a factor of 0.4 and then added to the last baseline value. This point in time in the acceleration signal was found to indentify FO. This method was found to consistently identify FO from accelerometer data when compared to the concurrently collected footswitch data and other bouts of walking across subjects and speed conditions.

To identify FC, the algorithm sought out to determine when (during terminal swing) there were large negative acceleration in the X-axis (Figure 2.4). This indicated that the foot was beginning to slow down in preparation for FC. Using the footswitches as a guide, the algorithm searched for the largest decelerations in data found between successive FO. Actual FC occurs after the end of this rapid deceleration (large negative slop in X-axis). Next, the algorithm differentiated data.
found between successive FO and identified the largest negativity in the signal. The minimum value at the negativity was found to be FC. This method of FC detection has been previously used in acceleration profiles from the lower leg and trunk (Kavanagh & Menz, 2008; Zijlstra & Hof, 2003).

Part 2: Validation of ABLE

To validate the accuracy of the ABLE system’s method to identify temporal gait events, data from the ABLE system was compared to footswitch data measured concurrently.

Participants: 6 healthy subjects were recruited (3 males; mean age ± SD: 26.9 years ± 4.6). Preliminary data demonstrated that acceleration profiles of healthy individual and individuals with stroke were shown to have similar waveform characteristics, with the exception of smaller amplitudes and longer gait cycle times for patients with stroke (Figure 2.6). For this reason, only healthy individuals were recruited to conduct this initial validation of the ABLE system. Ethics approval to conduct the study was provided by the Toronto Rehabilitation Institute’s Research Ethics Board. All subjects recruited were clear of any cognitive and/or neurological pathology that would affect their gait.

Protocol: The ABLE system was fastened to each ankle, just proximal to the lateral malleolus and footswitch (B&L Engineering, Santa Ana, CA) insoles were secured within each shoe. Subjects were instructed to walk along a 15m walkway at three different speeds (preferred, slow and fast) with three trials at each speed.

Analysis: The ABLE system was sampled at a rate of 50Hz as this was the present limit of the PDA based system. Footswitches were oversampled at1000 Hz to achieve millisecond resolution. FC and FO were indentified in both the footswitches and ABLE system. Using the method described in ‘Step-3: walking and gait event detection’ (above) FC and FO were determined from the ABLE system. Footswitches contained contacts at the heel and 5th metatarsal, which when closed signaled FC or FO, respectively. Successive FC (or FO) events (i.e. stride time) was independently calculated for both footswitches and the ABLE system. A difference score in stride time was calculated between the two measurement approaches and used as the dependent variable in subsequent analysis. A difference score of 0 would indicate a perfect
agreement in FC/FO time between the two approaches. A value ≥ 0 would indicate that footswitch detected FC/FO after ABLE system. Conversely, a value ≤ 0 would mean that the footswitch identified FC/FO prior to the ABLE system.

A ranked-transformed one-factor repeated measures analysis of variance (ANOVA) was separately carried out for FO and FC to examine speed (slow, preferred, and fast) main effects across subjects. Descriptive statistics were also conducted for each gait event, across three speed conditions. Statistical significant was indicated by a p<0.05.

2.3 Results

Part 1: Development & Feasibility: Figure 2.1 demonstrates the components of the ABLE system. Unexpected difficulties were experienced with Bluetooth connectivity between the PDA and accelerometer ankle units and with battery disconnection during some collection periods. It was observed that the PDA and accelerometers lost Bluetooth connection at unexplained instances during data collection. Once connection was lost, the signal between the PDA and accelerometer could not be independently re-established, resulting in lost data for the duration of disconnection (this problem has since been resolved to permit automatic re-establishing of communication). We speculated that there were two potential sources for this phenomenon; 1) transient loses in power supply (e.g. possible loose power connection which was confirmed in later testing) or 2) radio wave interference from the environment (e.g. Wi-Fi); but, we were unable to confirm the occurrence of the latter. With respect to the former, it was found that repeated battery use for data collection caused the wiring on the battery to become weak and therefore prone to committing transient shortages in power supply.

There were no incidences of skin irritation or accelerometer ankle-strap movement around the ankle reported by either healthy individuals or patients with stroke. The non-elastic material of the ankle-strap provided a snug fit without applying compression to the ankle and the inner foam lining did not allow the strap or the accelerometer to move out of place during collection. Although it was not an obstacle to data collection, all patients indicated some concern with respect to the size of the PDA. Patients indicated that although the ABLE system did not prevent them from performing their activities, they were consistently reminded that they were wearing
the ABLE system when transitioning to a seated/lying position because they were required move the PDA to a more comfortable position.

**Part 2: Validation:** Both methods of measurement identified the same number of steps for all task conditions for all subjects. There were no statistically significant differences in speed conditions for FC or FO conditions. Overall, we found that across the different speed conditions the mean difference scores for FC-FC stride time and FO-FO stride time were -0.004s SD 0.015 and 0.006s SD 0.028, respectively. Large variability in difference scores for individual trials grouped by speed (slow, preferred and fast) were observed. Individual trials ranged from 0.33s to 0.47s, -0.42s to 0.45s and 0.4s to 0.45s respectively for FO. For FC, individual trial difference-scores for slow, preferred and fast speeds ranged from -0.46s to 0.46s, -0.045s to 0.42s and 0.42s to 0.44s respectively.

### 2.4 Discussion

The ABLE system was developed with the objective of constructing an instrument that could be used to measure and record FO and FC from each limb during walking over an extended period of time to capture details of everyday walking activity. Overall, we found the ABLE system was able to reliably capture FO and FC events over an extended period of time with limited negative reactions (e.g. PDA difficulties) from patients with stroke. Development of the ABLE system was based largely on relatively inexpensive commercially available accelerometers and PDA. The only customized element of the system was the data collection and post-processing methods, which have more recently been improved upon using alternative methods of collection.

Prior to development, a significant concern regarding the implementation of the ABLE system was the potential negative response patients would have while wearing well-fitted ankle straps and a PDA around the waist for lengthy periods of time. We observed that subjects did not experience any discomfort for the duration of collection and were not obstructed during their natural gait movements while wearing the devices. Even when resting/sleeping in bed there were no reported problems with the ankle-straeps moving from their original position. It is likely that the absence of discomfort can primarily be attributed to the small size and wireless data transmission of the accelerometer unit, which allowed patients to move freely without being constrained and constantly reminded of the collection system affixed to their lower limbs. It was
observed that the PDA, which was the largest piece of the ABLE system, was the most distracting and difficult piece of equipment for patients to handle. Yet, the PDA was tolerated mainly because it could be moved around the waist by the patient depending on the positioning of the body. Despite the inconveniences the PDA generated, it was an essential part of the current system required to achieve our goals of collecting synchronized bilateral gait data, sampled at a sufficient sampling rate that spanned multiple hours. At present, most existing wireless accelerometer systems do not communicate with each other to provide tight temporal synchrony and as a result a common collection point remains important. Future developments of ambulatory monitoring systems will need to explore methods to reduce overall size, maintain data synchrony and independently collect data without a common reference point (e.g. PDA).

The difficulties experienced regarding connectivity between the accelerometer ankle units and the PDA was unexpected. Although wireless connection via Bluetooth is an overall reliable method of communication, it has been demonstrated that Wi-Fi signals apart of wireless networks and other radio waves may cause interference with Bluetooth leading to potential signal disconnection (Dai Ying-jun, 2008). The ABLE system was capable of re-establishing connection; however, this required a manual reset leading to some data loss. Disconnection between the PDA and accelerometers is a substantial concern as it has the potential to overlook periods of walking. To address this problem, more recent adaptations to the software have lead to an automatic reconnection and this has considerably reduced the occurrence of any lost data. Subsequent testing will need to focus on exploring alternative methods of communication on the same PDA platform to determine whether issues of disconnection were due to hardware or method of communication.

An important outcome of the present work was the overall accuracy demonstrated by the ABLE system to identify periods of walking. Mean difference-scores across speed conditions were low indicating that, on average, the ABLE system can accurately identify periods of walking independent of walking velocity. This is an important finding as prior ambulatory detection systems decrease in gait detection accuracy during slow walking speeds (Storti et al., 2008). Furthermore, since each FO/FC was identified through a series of conditions (e.g. bilateral, reciprocal acceleration profiles) the ABLE system was able to avoid false walking detection. False gait detection has been a concern for other accelerometer system based on a single leg or
trunk measurement (Jasiewicz et al., 2006); however the bilateral placement of ABLE avoids this problem. Although the ABLE system excelled at indentifying overall periods of walking activity and could clearly reveal the occurrence of steps there were some inconsistencies in the estimation of the timing of individual FO and FC events.

Despite the acceptable performance of averaged data for identifying FC and FO, the amplitude of variability was a concern with respect to the validity of our results. The large SD for FO and FC as well as large difference scores within independent trials reduced the predictive validity of the ABLE system in identifying the precise timing of individual foot fall events. However, we are able to accept this level of variability in our results because our methods focused on the capacity of the system to detect periods of walking and not characteristics regarding individual foot-falls. Importantly, there was no systematic bias in the mean difference scores reported. The latter minimized concern that we were using the wrong acceleration features to reflect FO and FC events, but does lead us to suspect that most of the variability observed is due to the inaccuracy and lack of sophistication in the algorithm used feature extract individual FO/FC. In the present study, the issue of reliability with respect to our methods was not addressed because the walking acceleration waveform (figure 2.6) was so distinct that the rules of our algorithm would not have any difficulty indentifying periods of walking between subjects (e.g. patients with stroke or healthy individuals) and speed conditions. Furthermore, visual inspection of superimposed footswitch and accelerometer data across individuals and speed conditions confirmed that on average, the temporal position of FO and FC indentified by the ABLE system closely predict the temporal positions of FO and FC indentified by the footswitches. Given the highlighted limitations, this initial methodological approach for the ABLE system is a valid approach to ambulatory monitoring particularly when focusing on the average of multiple step bouts (or periods) rather than individual step characteristics.

Future considerations for adaptation to improve the performance of the ABLE system include using a better method of communication between accelerometer units and PDA. Ideally, developing a device that can independently collect, record, and potentially synchronize data would reduce the need to transmit data to a central data logging device. To truly capture ‘everyday’ ambulatory activity, future devices would also have to increase the power capacity to ensure collection can occur for extended periods of time. By capturing a full 24-48 hours, we
would be able to better characterize full day behavior of patients. Extending data collection would also address questions regarding day-to-day variability in ambulatory activity. Increasing the duration of collection would also mean that future system would have to be waterproof so that patients would never need to take the accelerometer units off. The most substantial adaptation that is required for future systems would be better algorithms to feature extract FC and FO so that the margin of error between the actual and detected FO/FC would be within the error related to sampling rate. Collectively, these adaptations address a number of concerns about the ABLE system and improve the utility of future data collection.

Conclusions
The successful creation of the ABLE system bridges the gap between standard gait assessments and independent ambulatory monitoring systems to acquire temporal gait information. More specifically, we addressed the need for a temporally synchronized, bilateral measurement tool that was capable of acquiring relevant gait data over extended periods of time. The availability of detailed temporal information about walking to clinical practice may provide clinicians information that may help to augment post stroke recovery.
2.5 References


Table 2.1 Demographic and clinical characteristics of patients – Study 1. (BBS – Berg Balance Scale, CMSA – Chedoke McMaster Stroke Assessment, SPC - single point cane)

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Gender</th>
<th>Age</th>
<th>Days Post-Stroke</th>
<th>BBS</th>
<th>CMSA Leg</th>
<th>CMSA Foot</th>
<th>Preferred Gait Speed (s)</th>
<th>Walking Aid</th>
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<td>A</td>
<td>M</td>
<td>75</td>
<td>15</td>
<td>38</td>
<td>5</td>
<td>3</td>
<td>0.9</td>
<td>SPC</td>
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<td>47</td>
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<td>0.77</td>
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<tr>
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<td>F</td>
<td>45</td>
<td>75</td>
<td>53</td>
<td>4</td>
<td>3</td>
<td>1.06</td>
<td>SPC</td>
</tr>
</tbody>
</table>

Mean 62.4 62.4 62.4 0.944
Figure 2.1 Illustration of the ABLE (Accelerometry for the Bilateral Lower Extremities) system. 
A. demonstrates the Freescale MMA7260Q tri-axial accelerometer board used in the ABLE system. 
B. Demonstrates the overall size of the ABLE accelerometer unit compared to a two dollar coin. 
C. The back casing of the accelerometer unit is removed demonstrating where the battery is located during collection. 
D. The middle divider is removed in the accelerometer unit exposing the accelerometer board, booster board (used to increase voltage) and the connector to the battery. During normal data collection, the accelerometer board and booster board are concealed using the middle divider and the battery is concealed using the back plate (C).
Figure 2.2 Orientation of the ABLE system placed on the lateral malleolus. When the lower limb is perpendicular to the ground, +X is in the anterior direction in anterior-posterior plane. +Y is in the up direction, in the vertical plane. In the medial-lateral plane, the +Z direction is in the medial direction.
Figure 2.3 Post-processing transformation of data. Flow chart represents the transformation of data from collection to output. Data from the accelerometers are combined to be re-sampled, filtered and sorted for types of activities. An algorithm was applied to determine if periods of activity can be classified as walking by meeting a number of criteria (feature extraction criteria). A separate algorithm was applied to identify foot-off (FO) and foot-contact (FC) from acceleration profiles.
Figure 2.4 Events in raw acceleration data used for gait event detection. (A) Highlights the significant negative acceleration in the X-axis which represents the large deceleration of the lower limb prior to FC during terminal swing. This large deceleration was used to identify the onset of FC. (B) Highlights a local negativity in the Y-axis, which occurs during initial swing of the lower limb. This local negativity was used to help identify for FO.
Figure 2.5 Walking acceleration profile superimposed with footswitch data. Sample Footswitch data (shown in black) superimposed onto accelerometer data, shown in red (Y-axis) and blue (X-axis). The red circle and blue square markings represent the detected foot-off (FO) and foot-contact (FC) by the algorithm. Vertical black lines next to the red circle or blue square represent the FO and FC determined by the footswitches.
Figure 2.6 Walking acceleration profiles for the affected, unaffected and healthy limb. Acceleration profiles between the affected, unaffected and healthy limb have similar waveform characteristics that are used to identify periods of walking. Difference in profiles that do not affect the ability of the algorithm to indentify FO and FC include: decreased acceleration amplitude and increased walking cycle time (stride time) in the affected limb.
3.0 Experiment 2: A Novel Approach to Ambulatory Monitoring: Investigation into the Quantity and Control of Everyday Walking in Patients with Sub-Acute Stroke.

3.1 Introduction
There is theoretical support for the notion that the quantity of activity performed in everyday life is a potentially important determinant of recovery and overall health in individuals after stroke (Ivey, Macko, Ryan, & Hafer-Macko, 2005; Macko et al., 2005). Developing an understanding about the characteristics and potential therapeutic benefit of everyday activities remains an important frontier to maximize recovery and health after stroke, particularly for individuals in the early stages. Towards this end, the focus of the present work was to develop detailed understanding of the characteristics of walking activity within a rehabilitation facility among patients with sub-acute stroke.

Current understanding of walking activity after stroke is based on studies that have focused on documenting ambulatory activity monitoring using variations of a pedometer to report step count as a primary outcome measure (Haeuber, Shaughnessy, Forrester, Coleman, & Macko, 2004; Manns & Baldwin, 2009; Michael, Allen, & Macko, 2005; Michael & Macko, 2007; Mudge, Stott, & Walt, 2007; Shaughnessy, Michael, Sorkin, & Macko, 2005; Tudor-Locke & Bassett, 2004). While pedometer-based systems can provide an overview of activity with the total number of steps taken, many of these systems are limited in some regards including: 1) difficulty in detecting periods of slow walking characteristic of many stroke patients (Shepherd, Toloza, McClung, & Schmalzried, 1999); and 2) lack of specificity for walking, which means that non-stepping motions have the potential to be coded as a walking event. Specific to the present study, there are no commercial or published ambulatory monitoring instruments that provide precise temporal details of the characteristics of walking (e.g. detection of timing of individual foot falls and details regarding the duration and time of day for each walking bout). For these reasons, the ABLE system was developed and utilized in the present study over other commercially available activity monitors (Mudge et al., 2007).

Interest in the potential therapeutic value of everyday walking requires a better understanding of the detailed characteristics of walking beyond conventional measures of step count. For example,
speed and the duration of walking are more classically used as indices of the potential cardiorespiratory challenges linked to walking (Sibley, Tang, Brooks, & McIlroy, 2008). Alternatively, duration of individual bouts may provide a more natural reflection of a patient's endurance and potential link to independence and participation. This notion is supported by indices of walking capacity such as the 2 or 6 minute walk tests (6MWT) (Tang, Sibley, Bayley, McIlroy, & Brooks, 2006). The benefit of everyday walking as a potential method to practice and improve the control of walking is also of interest since task-dependent gait retraining is considered a potent method to facilitate recovery of walking (Turnbull & Wall, 1995). Measures such as detailed spatiotemporal indices for each step would be necessary to establish the ‘‘control’’ of everyday walking as a potential source of benefit to recovery. While measures of step count have provided an important understanding of overall activity patterns, more specific insight into the characteristics of quantity (e.g. temporal frequency and bout duration) and control of walking (e.g. temporal gait symmetry) would have added value for understanding the potential therapeutic benefit that may be derived from everyday walking.

In the present study, the primary objectives were to: 1) assess the quantity of walking, specifically measures of total time of walking and individual walking bout duration and frequency, and 2) evaluate temporal swing symmetry between a spatiotemporal gait assessment and everyday walking. For the purpose of the present study, ‘everyday’ walking was defined as any walking activity performed by the patient during the course of their inpatient day. Secondarily, we conducted a preliminary investigation in the link between such details of everyday walking activity and stroke severity (e.g. balance and sensorimotor control). To permit the assessment of these variables, we used a newly developed wireless, wearable measurement system called Accelerometry for the Bilateral Lower Extremities (ABLE) (Prajapati, Gage, Brooks, & McIlroy, 2008).

3.2 Methods

Patients: Eleven unilateral hemiparetic in-patients with stroke (8 male; mean age 64.5 ± 13.1; mean days post stroke 42 ± 25.6) were consecutively recruited from a university rehabilitation hospital. All individuals provided informed consent as approved by the Research Ethics Board of Toronto Rehabilitation Institute, Toronto, Ontario. Potential participants were first evaluated by members of the hospital staff physical therapy team; participants who were able to walk
independently with or without the aid of a single-point cane/rollator and could transfer without supervision were referred for participation in the study.

*Measurements:* Ambulatory Data Acquisition: The ABLE system (Prajapati et al., 2008) (Figure 3.1) was used for ambulatory data collection. The system comprised two Bluetooth enabled 3-axis WiTilt V2 accelerometers (Sparkfun Electronics, Boulder CO) and a PDA (Hewlett Packard hx2410) with custom developed software to acquire and log data from the accelerometers. Custom developed ankle sleeves were used to secure the accelerometer units just proximal to the lateral malleolus bilaterally by the investigator and the PDA was secured to the patient’s waist using a polyester belt and pouch. Three-dimensional accelerometer data were wirelessly transmitted to the PDA from each accelerometer unit, and recorded with a sampling rate of 50 Hz. Data were transferred from the PDA to a computer for storage and offline data processing.

*Gait Assessment:* Spatiotemporal characteristics of gait were collected using a GAITRite system (CIR Systems, Havertown PA) sampled at 30Hz. Patients walked across the mat at their preferred gait speed using their assistive devices. The number of walks over the mat was based on the objective to obtain at least 20 total strides. Severity of motor impairment was assessed using the Chedoke McMaster Stroke Assessment scale (CMSA) (Gowland et al., 1993). Balance was assessed using the Berg Balance Scale (BBS) (Berg, Wood-Duphine, & Gayton, 1989).

*Protocol:* Gait assessments were conducted 1-2 days prior to ambulatory monitoring. On the day of ambulatory gait data collection, routine morning activities were first completed (e.g. bathing, dressing and breakfast) before patients were fitted with the ABLE system. Once the system was fitted and collection began, the patient was left to perform their daily activities within the rehabilitation hospital. Periodically, at predetermined times (e.g. lunch), the investigator met with the patient to ensure there was no discomfort and all devices remained operational. The patient was provided a telephone extension to contact the investigator at any point throughout the measurement period. Data collection continued for approximately 8 hours (9 am to 5 pm), after which the ABLE system was removed from the patient.
Data Analysis:

Detecting Patterns of Walking Activity: Analysis of time series acceleration data was conducted to identify gait cycle events throughout the collection period. First, periods of reciprocal leg movement were identified to ensure periods of unilateral non-walking activities were omitted. Next, time series acceleration data were further examined to determine FC and FO. This was done by matching the patient’s acceleration profile to a known profile for walking (Prajapati et al., 2008). While individual steps were determined in the present study, we defined a bout of walking as a period of at least 10 consecutive steps. Individual bouts of walking were also differentiated by having a pause of at least 5 seconds before the next period of walking.

Gait symmetry: During gait assessment, the GAITRite system permitted the evaluation of temporal symmetry. Conversely, ‘everyday’ symmetry was calculated using FC and FO from each step taken during bouts of walking throughout the day. Both symmetry measures were calculated by taking the ratio between paretic swing time and non-paretic swing time (Patterson et al., 2008). In order to compare symmetry of everyday walking to that determined from standard gait assessment, we restricted the current comparison to only to periods of ‘steady-state’ walking. Therefore, we only considered periods of walking in which the swing times were within the mean (+/- 1 SD) of swing time measured from our gait assessment. A Wilcoxon t-test was conducted between measures of ‘everyday’ symmetry and gait assessment symmetry measures. Also, Correlation analysis (Pearson’s) was conducted between measures of walking quantity and stroke severity. Statistically significant associations were denoted by p<0.05.

Relationship to stroke severity: To establish the presence of an association between stroke severity and walking activity we conducted correlation analysis (Pearson’s) for measures of balance impairment (BBS) and nonparametric correlation analysis (Spearman’s) for motor impairment (CMSA) to the total walking time and average bout durations. Statistically significant associations were denoted by p<0.05.

3.3 Results

Patient Characteristics & Use of the ABLE System: Details of individual patient characteristics are provided in Table 3.1. With regard to the use of the ABLE system there were no reported cases of injury or discomfort to the proximal region of the ankles where the ABLE units were
affixed. Six of the 11 patients required an assistive device to walk and in one case a wheelchair was often used even though the individual was capable of walking independently. Total duration of data collected for patients B and G were shorter than other patients due to periods of disconnection between the ABLE units and the data logger. As a result, there were some periods of the day for which no data was collected. All patients participated in daily physical and/or occupational therapy with the exception of patient L who was not scheduled for occupational therapy on the day of collection.

**Quantity, Symmetry & Pattern of Walking Activity:** Measures of walking quantity for each patient are presented in Table 3.2. Mean total collection time for all patients was 461.2 min SD 49.6. Patients demonstrated an average of 52.6 min SD 30, or 11.3% SD 5.8% of the total collection period, of walking activity. The average number of total steps taken across subjects throughout the collection period was 4816 steps SD 3247. Patient E performed the greatest total time of walking activity with 112.7 min (20.8% of the collection time, total of 8730 steps); patient H performed the least amount of total walking activity with 8.95 min. (1.9% of collection time, total of 584 steps). This observation may be partly explained by the fact that patient H was more reliant on the use of a wheelchair. This particular patient had only recently achieved the capacity to independently ambulate (within 3 days). All other patients had been independently walking for at least 7 days prior to testing.

Details of the quantity of walking activity, expressed as the frequency and duration of walking bouts recorded throughout the day for the most active patient (138 bouts) and least active patient (7 bouts) are presented in Figure 3.2. The average duration for bouts of walking performed for all patients was 59.8s SD 23.4. Longer walking bouts were associated with walking to and from patient rooms to the structured therapy sessions and the longest bouts occurred during functional walk testing while in structured therapy. Structured therapy was defined as periods of time that reflects organized, supervised therapy, such as physical and occupational therapy and activities planned by other health professionals. Patient activity records were used to determine the total amount of therapeutic walking time (walking during structured therapy) (see Table 3.2). These periods ranged from 3.45 min to 29.5 min Patients J and L demonstrated the longest duration of therapeutic walking activity with 29.5 min and 23.2 min respectively. These observations were due in part to the patients’ participation in an ongoing aerobic exercise intervention program.
Consequently, while wearing the ABLE system, patient L performed a 6MWT once and subject J performed the 6MWT twice. Both patients B and L self-reported “smoking” as an influence for increased walking outside of therapy because these patients were required to walk to and from a designated smoking area outside of the hospital.

A significant relationship was observed between ‘everyday’ temporal swing symmetry and symmetry from standard gait assessments (p=<.05). More specifically, symmetry observed (Table 3.1 & 3.2) revealed that 10 of the 11 patients were either the same or more asymmetrical (i.e. worse) during their ‘everyday’ walking compared to their gait assessment symmetry values. Symmetry values calculated from gait assessments were within normative values (0.9 – 1.1) (Patterson et al., 2008) for all subjects. In contrast, only 8 of the 11 patients had symmetry values within normal ranges for ‘everyday’ values (Figure 3.3).

Association Between Stroke Severity & Quantity of Everyday Walking: A summary of association analysis comparing measures of stroke severity and everyday walking is provided in Table 3.3. Overall, there were no statistically significant associations between motor and balance impairment and the quantity of walking activity. Although not statistically significant, results also revealed a modest inverse trend between CMSA foot score and walking time (r=-0.47, p=0.147) and between BBS and total inactivity time (r=-0.48, p=0.136).

3.4 Discussion

Few studies have examined ‘everyday’ ambulatory activity in patients with stroke (Haeuber et al., 2004; Manns & Baldwin, 2009; Michael et al., 2005; Michael & Macko, 2007; Shaughnessy et al., 2005) and fewer have specifically attempted to examine details regarding the quantity and temporal symmetry of walking in patients during their inpatient stay, possibly due to limitations associated with technology and cost of data acquisition. As far as we are aware, this is the first study to provide both overall measures of ‘everyday walking’ (e.g. step count) as well as detailed temporal information (e.g. bout duration, temporal gait symmetry) among those in active rehabilitation in the sub-acute phase of recovery.

Consistent with previous reports (Haeuber et al., 2004; Manns & Baldwin, 2009; Michael et al., 2005; Michael & Macko, 2007; Shaughnessy et al., 2005), the present study confirms the
relatively low volume of ambulatory activity in patients with stroke observed during inpatient stay and to a lesser extent in the community. Based on the assessment of ambulatory activity classified by step count for patients with chronic stroke (Tudor-Locke & Bassett, 2004), six patients in the present study would be classified as ‘sedentary’ (<5000 steps/day), two patients would be considered ‘low active’ (5000-7499 steps/day) and three patients would be considered ‘somewhat active’ (7500-9999 steps/day). However, as this study has demonstrated, patients within a classification category are highly variable with respect to their pattern of walking activity (e.g. frequency and duration). For example, upon closer examination we found that the majority of walking activity for some patients is generated by one or two extended bouts of walking within physical therapy, resulting in large periods of inactivity for the remainder of the day. Despite the low overall step count, the reported values are found to be nearly double the previously reported values for patients in the community (Haeuber et al., 2004). The environment and surroundings of patients in the community, which can influence the quantity of walking behavior, is not detailed in such studies so it is difficult to speculate the basis for a reduction in step count. Some of the difference may also be attributed to the current focus on the time of day for data collection (i.e. 8-5pm), most likely the most active period of the day. More generally, patient classifications based on overall step-count measures provide a superficial characterization of patient ambulatory activity.

As noted the focus of the current work was to provide additional details for the pattern of walking. Step count may provide some indication of total walking activity; however, it is specifically important to understand the duration of walking bouts as this may have an import link to endurance, fatigue (Sibley et al., 2008) and potential benefits to overall health, including cardiovascular fitness. Consequently, an important finding in this study is that when patients were active and walking, they did so for very short durations, on average less than a minute. Reported bout durations in this study are far lower than the mean 3.3 minute duration reported by Manns and Baldwin (Manns & Baldwin, 2009). The notable dissimilarity between our results and those previously reported may be due to how bout duration was defined, and the ability to specifically isolate bipedal walking from other events that would trigger walking activity counts. The current approach relies both on the pattern of acceleration and the association between profiles from both lower limbs to confirm walking. Other methods of gait detection (including Manns and Baldwin) relied on single limb measurement techniques which may be prone to
misidentifications (false positives). An important finding that had direct clinical implications is that individual bout durations (30 to 90 s) and patient activity logs reveal that bouts of walking are more likely associated with completing basic functional goals necessary for daily living. Therefore, patients may not be generating adequate intensities of walking to stimulate improvements to cardiovascular functioning (Gage et al., 2007). Future work should look into the cardiovascular responses of everyday walking activity as an index of intensity of walking and possible therapeutic benefits.

The capacity to compare differences between gait symmetry measured during a standard gait assessment and ‘everyday’ gait symmetry was unique to this study. We found that gait symmetry was more asymmetrical (i.e. worse) during ‘everyday’ gait compared to their standard gait assessment. By restricting the analysis of only steady state walking (both lab and everyday) we reduce the possibility that differences were associated with gait initiation, turning or navigating obstacles. Therefore, observed differences may be explained by the fact that during standardized gait assessments patients were on their ‘best behavior’ and when they walk independently during the course of the day, they regress back to a preferred asymmetric gait pattern.

Limitations of the present study include disproportional sample of males and females and an overall small sample size, both of which may have contributed to significant inter-patient variability in indices of stroke severity and an absence of associations as seen in previous studies (Michael et al., 2005; Michael & Macko, 2007). While one might presume that motor and balance impairments may be the most prominent determinants of ambulatory activity, there is considerable variability in the pattern of walking activity that does not seem accounted for by impairment levels. Other factors contributing to large variability in the pattern of walking include the institution environment (e.g. distance from room to therapy areas), presence of caregivers/visitors, and unique reasons for walking (e.g. going outside to smoke). One of the more substantial limitations of the present study is the absence of healthy control data with respect to bout duration. Although no data on health controls are available for comparison, the occurrence of short bout durations in patients residing in rehabilitation units is concerning since one might argue that in such a rehab setting patients should be engaging in greater amounts of overall walking.
Conclusions
There are several important clinical applications made possible by the ABLE system that are beyond the objectives of the present study. First it may be used to help therapists guide appropriate increases in the dose of activity by providing a method to monitor treatment outcomes. In addition, it could be operated as a ‘homework-checker’ to ensure prescribed amounts of daily walking activity is actually performed. Overall, it is our view that wireless monitoring systems, such as the ABLE system, have the potential to provide additional, valuable additional temporal information about walking activity. Such information is beneficial for both therapist and patients within an in-patient environment to promote and facilitate activity patterns that are conducive to greater recovery.
3.5 References


Table 3.1 Demographic and clinical characteristics of patients- Study 2. * denotes the use of a single point cane during clinical gait evaluation and † denotes the use of a rollator. (MCA = middle cerebral artery, BBS – Berg Balance Scale, CMSA – Chedoke McMaster Stroke Assessment).

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Gender</th>
<th>Type of Stroke</th>
<th>Lesion Location</th>
<th>Age</th>
<th>Days Post Stroke</th>
<th>CMSA Leg</th>
<th>CMSA Foot</th>
<th>BBS</th>
<th>Gait Speed (m/s)</th>
<th>Symmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>M</td>
<td>Hemorrhagic</td>
<td>Right basal ganglia</td>
<td>75</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>37</td>
<td>0.9</td>
<td>0.99*</td>
</tr>
<tr>
<td>B</td>
<td>M</td>
<td>Hemorrhagic</td>
<td>Right posterior lentiform nucleus</td>
<td>62</td>
<td>27</td>
<td>4</td>
<td>4</td>
<td>47</td>
<td>0.77</td>
<td>1.01</td>
</tr>
<tr>
<td>C</td>
<td>M</td>
<td>Ishemic</td>
<td>Right MCA</td>
<td>54</td>
<td>91</td>
<td>7</td>
<td>6</td>
<td>27</td>
<td>0.59</td>
<td>1.02</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>Ishemic</td>
<td>Left occipitoparietal lobe</td>
<td>76</td>
<td>18</td>
<td>5</td>
<td>6</td>
<td>50</td>
<td>1.48</td>
<td>0.97</td>
</tr>
<tr>
<td>E</td>
<td>F</td>
<td>Ishemic</td>
<td>Right frontal lobe</td>
<td>45</td>
<td>75</td>
<td>4</td>
<td>3</td>
<td>53</td>
<td>1.06</td>
<td>1.04*</td>
</tr>
<tr>
<td>F</td>
<td>M</td>
<td>Ishemic</td>
<td>Left MCA</td>
<td>76</td>
<td>30</td>
<td>6</td>
<td>3</td>
<td>48</td>
<td>0.8</td>
<td>0.97</td>
</tr>
<tr>
<td>G</td>
<td>M</td>
<td>Ishemic</td>
<td>Left MCA</td>
<td>78</td>
<td>46</td>
<td>6</td>
<td>5</td>
<td>49</td>
<td>0.82</td>
<td>1.00</td>
</tr>
<tr>
<td>H</td>
<td>M</td>
<td>Ishemic</td>
<td>Right MCA</td>
<td>80</td>
<td>70</td>
<td>6</td>
<td>4</td>
<td>37</td>
<td>0.31</td>
<td>0.99†</td>
</tr>
<tr>
<td>J</td>
<td>F</td>
<td>Ishemic</td>
<td>Left inferior pons</td>
<td>47</td>
<td>33</td>
<td>3</td>
<td>4</td>
<td>33</td>
<td>0.31</td>
<td>0.94*</td>
</tr>
<tr>
<td>K</td>
<td>F</td>
<td>Ishemic</td>
<td>Left frontal and parietal lobe</td>
<td>63</td>
<td>31</td>
<td>3</td>
<td>4</td>
<td>25</td>
<td>0.49</td>
<td>1.10*</td>
</tr>
<tr>
<td>L</td>
<td>M</td>
<td>Ishemic</td>
<td>Left temporofrontal</td>
<td>54</td>
<td>31</td>
<td>6</td>
<td>6</td>
<td>49</td>
<td>0.75</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Mean: 64.5  42  0.80
SD: 13.1  25.6  0.34
Table 3.2 Summary of walking measures collected throughout the day. Patients B and G, indicated by *, have a shorter collection time due to temporary periods of wireless disconnect between the ABLE system and data logger. † indicates patients requiring a single-point cane during the day and the ‡ indicates those patients requiring a rollator.

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Collection Time (min)</th>
<th>Total Walking Time (min) (%)</th>
<th>Total Structured Walking (min) Bouts</th>
<th>Total Steps</th>
<th>Mean Bout Duration (s)</th>
<th>Temporal Swing Symmetry (SD) 95% CI</th>
<th>Cadence (steps/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>448.60</td>
<td>38.7 (8.5)</td>
<td>6.23</td>
<td>41</td>
<td>3077</td>
<td>1.12 (0.09) †</td>
<td>0.93-1.31</td>
</tr>
<tr>
<td>B</td>
<td>333.65*</td>
<td>20.3 (6.1)</td>
<td>-</td>
<td>38</td>
<td>1735</td>
<td>1.09 (0.14) †</td>
<td>0.81-1.37</td>
</tr>
<tr>
<td>C</td>
<td>468.50</td>
<td>23.8 (5.1)</td>
<td>3.45</td>
<td>42</td>
<td>1574</td>
<td>1.09 (0.14) †</td>
<td>0.82-1.36</td>
</tr>
<tr>
<td>D</td>
<td>421</td>
<td>41.7 (9.9)</td>
<td>13.40</td>
<td>71</td>
<td>3025</td>
<td>1.04 (0.13)</td>
<td>0.78-1.30</td>
</tr>
<tr>
<td>E</td>
<td>542.80</td>
<td>112.7 (20.8)</td>
<td>23.20</td>
<td>138</td>
<td>8730</td>
<td>1.05 (0.07) †</td>
<td>0.91-1.18</td>
</tr>
<tr>
<td>F</td>
<td>456.50</td>
<td>71.6 (15.7)</td>
<td>18.40</td>
<td>46</td>
<td>6020</td>
<td>0.97 (0.04)</td>
<td>0.88-1.05</td>
</tr>
<tr>
<td>G</td>
<td>366.50*</td>
<td>64.7 (17.7)</td>
<td>-</td>
<td>39</td>
<td>5585</td>
<td>0.99 (0.06)</td>
<td>0.86-1.12</td>
</tr>
<tr>
<td>H</td>
<td>477.30</td>
<td>8.95 (1.9)</td>
<td>8.95</td>
<td>7</td>
<td>584</td>
<td>1.07 (0.17) ‡</td>
<td>0.73-1.41</td>
</tr>
<tr>
<td>J</td>
<td>581.30</td>
<td>60.2 (10.4)</td>
<td>29.50</td>
<td>48</td>
<td>3816</td>
<td>1.12 (0.14) ‡</td>
<td>0.85-1.39</td>
</tr>
<tr>
<td>K</td>
<td>504.40</td>
<td>78.3 (15.5)</td>
<td>9.50</td>
<td>89</td>
<td>8873</td>
<td>1.17 (0.12) ‡</td>
<td>0.94-1.40</td>
</tr>
<tr>
<td>L</td>
<td>472.50</td>
<td>58.4 (12.4)</td>
<td>25.40</td>
<td>60</td>
<td>9965</td>
<td>1.07 (0.12)</td>
<td>0.84-1.30</td>
</tr>
</tbody>
</table>

Mean 485.90 52.6 14.40 56.3 4816.7 59.8 84.7
SD 49.60 30 9.20 34.1 3247.2 23.4 9.13
Table 3.3 Summary of correlation analysis between quantity of walking and stroke severity. (BBS – Berg Balance Scale, CMSA – Chedoke McMaster Stroke Assessment)

<table>
<thead>
<tr>
<th>Quantity of Walking</th>
<th>Stroke Severity Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMSA – Leg</td>
</tr>
<tr>
<td>Total Walking Time</td>
<td>-0.36</td>
</tr>
<tr>
<td>Average Bout duration</td>
<td>0.22</td>
</tr>
<tr>
<td>Total Inactivity Time</td>
<td>-0.01</td>
</tr>
<tr>
<td>Total bouts</td>
<td>-0.43</td>
</tr>
</tbody>
</table>
**Figure 3.1** Placement of ABLE system on a patient. A Personal Digital Assistant (PDA) data logger was placed around the waist (A), and custom ankle sleeves, housing each ABLE unit, were affixed to each ankle just proximal to the lateral malleolus (B). Note: The object on the right wrist is a security device unrelated to the ABLE system.
Figure 3.2: Frequency profile of patient walking throughout the day. On the x-axis, time of day indicates when each individual bout of walking was performed. The relative durations of walking bout is represented by the y-axis. Structured therapeutic sessions are shaded in. Plot A presents the walking profile of patient E who walked the most. In contrast, plot B profiles patient H who walked the least.
Figure 3.3 Comparison between day-long symmetry and clinical symmetry. Figure illustrates the difference between clinically evaluated temporal swing symmetry and the mean and 95% confidence interval (CI) for temporal swing symmetry observed in bouts of walking over the course of the day. The range of normal temporal symmetry for healthy individuals is shown by the horizontal dashed lines.
4.0 Experiment 3: Cardiovascular Responses Associated with Everyday Walking in Sub-Acute Stroke

4.1 Introduction

Following stroke, a large portion of active rehabilitation is directed to regaining and promoting walking activity with less emphasis placed on improving the cardiorespiratory fitness of patients. Emerging studies have highlighted the extent to which patients are aerobically de-conditioned and the importance of increasing aerobic exercise post-stroke (Ivey et al., 2006; Tang, Sibley, Brooks, Thomas, & McIlroy, 2004); however, there have only been studies that independently investigated walking activity and cardiorespiratory response to activity in in-patient with stroke (Gage et al., 2007; Manns & Baldwin, 2009). Understanding such a relationship would be an important step towards determining if activity-specific cardiovascular loads are potentially beneficial or limiting to post-stroke recovery. With respect to everyday walking activity, in-patients with stroke have been shown to engage in low quantities of overall walking activity compared to healthy adults and stroke survivors in the community (Lincoln, Willis, Philips, Juby, & Berman, 1996). With regards to cardiovascular response to everyday activity, a positive association between activity intensity and cardiovascular responses has been reported in patients with stroke (Gage et al., 2007). While this latter study reported modest increases in heart rate responses (< 29 above resting HR) while patients engaged in everyday activities (Gage et al., 2007), there was no close temporal coupling of the HR response and the periods of physical activity that would truly inform about task-related influences on HR.

The current study is focused on detailing cardiovascular responses specifically linked to periods of ‘everyday’ walking in patients with sub-acute stroke residing in an in-patient rehabilitation facility. The rationale for this study is twofold. First, there is convincing evidence that increasing the frequency of aerobic exercise after stroke contributes to both sensorimotor and cardiorespiratory recovery (Ivey, Hafer-Macko, & Macko, 2006; Tang et al., 2004). Activities that contribute towards improving cardiovascular functioning primarily emerge from structured training programs; however improvements to aerobic benefits may be possible from walking activities that individuals with stroke engage in everyday life. Presently, it is not known whether in-patients, when outside of periods of structured therapy, engage in episodes of walking that serve as therapeutic aerobic exercise. Secondly, it is also not presently known whether everyday
walking may be too demanding for some patients with stroke leading to an elevated cardiovascular load that could potentially limit their participation in walking activity. Such speculation for the latter has been based on the well-reported inefficiencies of post-stroke gait (Zamparo, 1995; Bernardi et al., 1999). As a result, the focus of the present work is to explore the heart rate (HR) response temporally linked to periods of walking to determine if walking: 1) meets the recommended cardiorespiratory intensity (i.e. HR response) and duration necessary for therapeutic aerobic exercise (Franklin et al., 2000) and/or 2) greatly exceed such recommendations leading to a potential barrier to participation in walking activity.

Studies have indicated that de-conditioned patients with stroke may achieve a therapeutic training effect at intensities as low as 40% heart rate reserve (HRR) (Franklin et al., 2000; Roth, Merbitz, Mroczek, Dugan, & Suh, 1997). Physical activity performed at an intensity as low as 40% HRR can help contribute towards improving and maintaining cardiovascular fitness (Ivey et al., 2006; Potempa, Braun, Tinknell, & Popovich, 1996; Macko, Ivey, & Forrester, 2005). For these reasons, cardiovascular responses specifically linked to walking can be viewed as important complementary information that may help guide clinical decision making.

In addition to the potential benefits of task-specific increases in cardiovascular responses there is also the concern that the cardiovascular load of everyday walking can be excessively high limiting walking capacity. Walking at an intensity exceeding 80% HRR begins to utilize anaerobic resources making bouts of walking difficult to sustain. Such a prediction may also be linked to the well reported inefficiencies of post-stroke walking (Zamparo, 1995) and may be a possible explanation for low volume of walking activity (Manns & Baldwin, 2009). Therefore, the current study not only explores if cardiovascular response during periods of walking reach beneficial, aerobic training levels (i.e. >40%HRR), but also if the cardiovascular response to walking reaches excessively high workloads that may lead it to becoming a barrier to walking.

The overall objective of the present study was to determine the characteristics of HR responses during bouts of everyday walking. Specifically, our primary objective was to 1) determine if peak amplitude of HR responses during bouts of walking reached intensities (40-60% of HRR) and durations (>10 min) necessary for therapeutic aerobic exercise (Franklin et al., 2000) and 2) determine if HR responses exceeded 80% HRR during everyday walking, which might reflect a
potential limitation on walking capacity. Secondly, we also sought to investigate whether there is a task-related HR response link to duration of walking as a possible reflection of limitations associated with elevated metabolic costs during walking. This examination is motivated in part by previous work revealing short mean bout durations among in-patients with stroke during everyday walking (Prajapati, Gage, Brooks, & McIlroy, 2008) and rapid increases in HR during the initial 2 min during standard functional walk tests, such as the six minute walk (6MWT) (Eng, Chu, Dawson, Kim, & Hepburn, 2002; Sibley, Tang, Brooks, & McIlroy, 2008).

4.2 Methods

Patients: Eight patients with stroke were consecutively recruited while residing in a teaching rehabilitation hospital. All individuals provided informed consent as approved by the Research Ethics Board of Toronto Rehabilitation Institute, Toronto, Ontario. Only patients who were able to walk independently, with no supervision required and with or without the use of a walking aid, were approached for recruitment. Since HR was a primary outcome, only those who were not taking HR altering medication (e.g. beta-blocker) were recruited to participate in the study.

Ambulatory & Heart Rate Data Acquisition: The ABLE system (Prajapati et al., 2008) (Figure 4.1) was used for ambulatory data collection. Custom developed ankle sleeves were used to secure the accelerometer units just proximal to the lateral malleolus bilaterally by the investigator and the PDA (data logger) was secured to the patient’s waist using a polyester belt and pouch. Data from each accelerometer unit were recorded at a sampling rate of 50 Hz. A Polar HR monitoring system was worn concurrently to acquire and record HR. The HR chest-strap was affixed to the patient’s chest, distal to the sternum and a data logger watch was placed on the patient’s non-paretic wrist and data was sampled at 0.2 Hz.

Clinical Assessment: Spatiotemporal characteristics of gait were collected using a GAITRite system (CHIR Inc, Havertown, PA) sampled at 30Hz. Patients walked over the mat at their preferred gait speed. The number of walks over the mat was based on the objective to obtain at least 20 total strides. Motor impairment was assessed using the Chedoke McMaster Stroke Assessment scale (CMSA) (Gowland et al., 1993). Balance was assessed using the Berg Balance Scale (BBS) (Berg, Wood-Duphine, & Gayton, 1989).
**Protocol**

On the day of ambulatory gait data collection, after routine morning activities were completed (e.g. bathing, dressing and breakfast), patients were fitted with the ABLE and HR monitoring systems (see measurements) and left to perform their daily activities. Every 1-2 hours, the investigator met with the patient to ensure there was no discomfort and all devices remained operational. Data collection continued for approximately 8 hours, between approximately 9 am and 5 pm, after which the collection systems were removed.

**Data Analysis**

*Walking Activity Detection:* Each step during periods of walking activity was identified in the present study; however, we delimited walking in our analysis to ‘bouts’ of walking. A bout of walking consisted of at least 10 consecutive steps, because shorter bouts would not likely have yielded a measurable HR response due to the short duration and due to HR being sampled every 5 sec (sampling frequency - 0.2 Hz). Individual bouts of walking were also differentiated by having a pause of at least 5 seconds before the next period of walking.

*Physiological Change Detection:* The Karvonen formula (Karvonen, Kentala, & Mustala, 1957) was modified in the present study to determine the % intensity (i.e. % of heart rate reserve \( [HRR] \)) during bouts of walking. Using HR collected from the heart rate monitor (HR\(_{observed}\)) the \( %HRR \) was determined for each bout of walking by using the following modified Karvonen formula:

\[
%HRR = \left( \frac{[HR_{observed} - HR_{rest}]}{[HR_{max} - HR_{rest}]} \right) \times 100
\]

\( HR_{max} \) was determined by using the equation: \( HR_{max} = 220 - \text{age of subject} \). Resting HR was determined to by using the lowest HR within a 10 minute period just prior to full day collection. For each identified bout of walking, HR response (HR\(_{observed}\)) for that specific bout was determined by averaging the three highest, consecutive HR measures within the bout. This approach was taken in order to acquire a sustained HR response over 15s (e.g. 3 HR measurement points). This method of was used in contrast to using a single point \( HR_{max} \), which has the potential to identify transient mutant HR responses.

*Link Between Walking Activity & Heart Rate Response:* Data were independently collected from both the ABLE and Polar collection systems. Data collected from the two systems were initiated
simultaneously to ensure they were temporally synchronized. Using custom software, data were aligned using the timestamp at the beginning of the Accelerometry data and the first measurement point from the heart rate data. To identify changes in HR during bouts of walking, only HR data during identified periods of walking were extracted and analyzed from day long measurements. According to guidelines for therapeutic activity (Franklin et al., 2000), bouts of therapeutic walking require a minimum duration of 10 min with at least 40 % of HRR during that time.

Association between HR Response & Duration of Walking: Previously reported (Prajapati et al., 2008) mean bout durations for patients in an inpatient care unit were found to be less than 1 min in duration during everyday walking. For this reason, bouts of walking in the present study were further separated into 15s intervals to progressively demonstrate potential HR changes to duration of walking. Correlation analysis (Pearson’s) between %HRR and duration were conducted for each individual bout of walking and for %HRR across each time interval.

4.3 Results
Clinical and demographic characteristics of patients recruited are detailed in Table 4.1 and walking characteristics are outlined in Table 4.2. Data were collected, on average, from both the ABLE and Polar systems for 8.41 hrs SD 0.8 over the span of a single inpatient day. Average gait speed and cadence during clinical assessment for all patients were 0.7 m/s SD 0.33 and 88.2 steps/min SD 14.4, respectively. There were no reported cases of injury or discomfort to either the proximal region of the ankles where the ABLE units were affixed or to the chest region where the HR monitor was fitted. Six of the eight subjects required a walking aid during both everyday and clinical data collection.

Did Patients Meet Recommended Physiological Intensities & Durations for Aerobic Exercise During Everyday Walking? Mean %HRR for bouts of walking was 19.4 %. Of the 8 patients tested, only patients B and E exhibited bouts of walking that exceeded 40%HRR. The remaining patients did not present walking intensities above 40%HRR in any of their bouts (Figure 4.2). Patient B had the largest number of bouts over 40%HRR with 31 bouts or 93% of their total bouts, while patient G exhibited 3 bouts or 3.3% of their total bouts over 40%HRR. Excluding patient B from analysis due to their relatively large %HRR response, the mean %HRR found in
all other patients during everyday walking was 15.5%. Patient H demonstrated the lowest mean %HRR at 8.9% and patient B demonstrated the highest mean with 59.3%. According to the criteria for therapeutic exercise, none of the patients were able to fulfill both requirements of duration (intervals $\geq 10$ min) and intensity ($%\text{HRR} \geq 40\%$).

**Did Patients Exceed Recommended Physiological Intensities During Everyday Walking?** With respect to bouts of walking exceeding 80%HRR, only 1 patient, patient B, surpassed this mark with 3 bouts, or 9% of their total bouts ranging from 85.8% to 97.5%HRR. These bouts were not long in duration (34, 37, and 58s) and were not performed at high cadences (70, 74, 74 steps/min); however, these bouts were performed while the patient walked (with a rollator) on the sidewalk outside the rehabilitation hospital under the supervision of a therapist. All other patients exhibited their respective max %HRR below the 40% threshold, with the exception of patient G who had a max %HRR of 42%.

**Characteristics of Everyday Walking:** The average number and duration of bouts identified throughout the collection period were 62.6 bouts SD 21.4 and 57.1s SD 31.6 (Table 4.2). Overall, 80.8% of all walking bouts recorded were less than 1 min in duration and only 1.8% of all bouts were greater than 5 min. Average step count was 3708 steps SD 1452 over the 8 hour period. Patient B had the lowest number of walking bouts with 33 (1774 steps), while patient E demonstrated the greatest number of walking bouts with 91 (4778 steps). The single longest bout duration was 13 min by patient F. With the exception of patients C and E, all patients recorded their longest respective bouts during the course of structured therapy (e.g. physical therapy).

Both tables 4.1 & 4.2 highlight, cadence during day-long measurements compared to clinical assessment. In 4 subjects (C, D, E, G) average cadence was lower in day-long walking and in the other 4 patients (A, B, F, H) the cadence was higher for day-long walking. However, the differences for the former group (-17.7, -15.4, -13.4, and -3.5 steps/min) were larger than the latter (+0.4, +12, +5.6+ and +1.6 steps/min). It is noteworthy that patient B has the lowest total walking time, number of bouts, step count, BBS and preferred walking speed. Also, patient B was given consent by their therapist to begin independently ambulating with a walking aid after having been limited to a wheelchair since the onset of their stroke. The recent transition almost certainly reflected on their limited walking capacity at the time of testing.
Association between HR Response & Duration of Walking: Overall, there did not appear to be a positive or negative association between mean % HRR and duration of walking. For each subject, Figure 4.2 plots the relationship between mean %HRR during each bout of walking and duration of walking. To determine if there was a HR response within individual bouts of walking for each subject, we specifically correlated peak heart rate response to duration of walking for each bout (binned into 15s intervals). There were no statistically significant associations within any patients (-0.20 < r < .08).

4.4 Discussion
The present exploratory investigation sought out to determine the extent to which patients met the recommended intensities of physical activity (i.e. walking) or exceeded throughout the day while residing in an inpatient facility. Both the quantity and intensity/duration of everyday walking can have the potential to positively or negatively influence post-stroke recovery. Therefore, information obtained from the present study provides some basis for understanding the potential therapeutic value of everyday walking and also understand what specific adaptations to current rehabilitative practices can be made to maximize the time spent during in-patient rehabilitation.

Patients Do Not Meet Recommended Intensities During Walking Activity: It was unknown whether patients in the present study had the capacity to participate in walking that could generate an elevated cardiorespiratory response. However, given the ambulatory independence of patients and the rehabilitation-focused environment in which patients were in, it was anticipated that the intensity and duration for a small subset of walking bouts over the course of a day would reach therapeutic guidelines for aerobic exercise training. Yet, only 3.1% of all bouts detected, occurring in only two patients, were found to be above 40%HRR. Mean %HRR for everyday walking was 19.4%, consistent with %HRR of walking found in patients with stroke monitored during physical therapy (Kuys et al., 2006). Overall, both the duration and intensity of walking, determined by heart rate, did not approach the recommended guidelines for therapeutic walking during periods of structured (e.g. physical) therapy or unstructured/supervised time. The current study was a single day snapshot of everyday walking and as a result may limit the likelihood of observing extended bouts of walking that may have therapeutic value to cardiovascular health.
Guidelines for aerobic training exercises, such as walking, suggest a frequency of 3-5 times a week and if any of the individuals tested were engaged in such walking program, they may have been missed with this single day of measurement. Yet with this in mind, the low level of activity (e.g. bout duration and total steps) and the low intensity (low %HRR) for in-patients residing in a rehabilitation facility is striking. The absence of therapeutically beneficial walking activity may be attributed factors such as short durations, low walking speeds and the purpose for which patients walked. It is likely that low walking duration and low intensity levels may well be associated with more conventional walking activities (e.g. walking associated with activities of everyday living for controls and/or patients). However, one might expect that the post-stroke rehabilitation experience may provide a greater probability of increased activity, both during structured and unstructured periods of the day as this is a fundamental objective for in-patient rehabilitation. In this regard the opportunity to measure such associations in patients would seem a most usual source of information to therapists to guide treatment decisions regarding walking exercise programs.

**Excessive Walking Related Cardiovascular Load Does Not Limit Walking Duration:** An equally important inquiry was to determine if cardiovascular load was a potential limiter to walking duration. As noted the occurrence of heart rate responses greater than 80% HRR was rare and occurred in only 1 patient, patient B. Also, there was no positive association between heart rate response and walking duration. In the case of patient B, the patient had been given permission by their therapist to walk independently only one day prior to the time of testing. As a result, their poor walking and balance competency may have continued to compromise and limit their walking. Such challenges in control may have lead to an elevated heart rate response while walking and thus it may be possible for their walking to be limited by the physiological cost of walking (Zamparo, 1995; Bernardi et al., 1999). It may also is possible that the relatively low total quantity of walking is not of cardiovascular origin, but due to the patients low balance and gait speed which has been shown to strong associated with the quantity of walking (Michael et al., 2005).

With respect to heart rate and duration, we suspected there might be an increase in %HRR during more extended bouts of walking due to the greater mechanical energy cost associated with each stride in patients with stroke compared to healthy individuals at similar speeds (Chen, Patten,
Kothari, & Zajac, 2005). However, we found no such association between %HRR and duration of walking as our results reflect walking which was executed for the purposes of everyday activities performed at intensities well within the work load tolerances of each individual. Our data does contrasts the early sharp increase in HR found during the initiation (i.e. 2 min) of a functional walk tests (Eng et al., 2002; Sibley et al., 2008), which leads us believe that completing walking tasks related to ADL are performed at much lower intensities (e.g. cadence) than timed walk tests intended to challenge walking capacity. The relationship between HR and walking is very much dependent on the intensity of walking (e.g. cadence), since lowering walking cadence is a strategy used to conserve energy and reduce the amount of stress placed on the cardiovascular system (Detrembleur, Dierick, Stoquart, Chantraine, & Lejeune, 2003).

Characteristics of Everyday Walking: Overall, the low amounts of total walking observed are consistent with previously reported values (Manns & Baldwin, 2009; Michael et al., 2005; Prajapati et al., 2008). As our prior study has also indicated (Prajapati et al., 2008), durations of walking throughout an inpatient day primarily consists of short bouts (e.g. less than one minute). Although there were no data available on healthy individuals for comparison, it is possible that short durations of walking activity observed may not just be specific to patients with stroke, but more broadly reflects common walking patterns for inside environments. Therefore, bout durations observed reflect a patient’s participation and engagement in activities of daily living (ADL) rather than the extent of their functional impairments. For example, patients who were transferred from inpatient care to the community were found to have greater bout durations in the community, amounting to an extra 30 min of activity per day (Manns & Baldwin, 2009). Such an increase may be attributed to improvements to walking capacity but also to an expansion in space and adjustments to living in the community (Manns & Baldwin, 2009).

Clinical Significance: Profiling the relationship between ambulatory activity and HR response can have important health-related implications to post-stroke rehabilitation. The absence of activity that benefits cardiorespiratory health and fitness during supervised and unsupervised periods of the day highlight a larger problem associated with conventional in-patient care. These results can be viewed as a missed or lost opportunity for supplementary rehabilitation. Although the optimal dose of unstructured everyday walking that may best help augment sensorimotor recovery is still unknown, our view is that presumably a greater volume of walking at the
appropriate intensity and duration than presently recorded would be beneficial towards advancing recovery. The measurement approach used in the present study can help clinicians identify the absence of walking bouts that match guidelines for therapeutic benefits to augment structured rehabilitation programs. It can be argued that simply requesting patients to engage in additional walking activities outside of therapy may not occur or may at inadequate intensities or durations to provide meaningful improvements to cardiovascular health. Therefore, additional emphasis needs to be placed on increasing the intensity of walking activity as well as the addition of aerobic training programs as a part of standard care. Feasibility studies have demonstrated that such exercise programs can be implemented safely and without any negative effects on the effectiveness of conventional therapy (Tang et al., 2004). Furthermore, patients receiving aerobic training in addition to standard care have significant improvements in indices of neuromuscular control and functional ambulation (Tang et al., 2004). With the ability to monitor patient activity without a therapist present, it is possible to not only develop methods to extend the reach of rehabilitation practice beyond the standard allotted time of care, but to also ensure prescribed amounts of activity are being performed. Emphasizing additional therapy-guided activities throughout the day may be one method to better address ‘down’ time frequently experienced by patients (Bernhardt, Dewey, Thrift, & Donnan, 2004; Gage et al., 2007). Future studies will need to examine patient activity across multiple days to develop a better understanding of patient activity levels and the factors that influence them. In addition, the potential use of bout duration and its associated physiological response as an outcome measure for clinical practice requires further study (Manns & Baldwin, 2009).

**Conclusions**
This preliminary investigation between walking specific activities and associated physiological responses provides important insight into the physiological demands placed by walking on patients residing in a rehabilitation hospital. These results indicate that everyday walking associated with ADL does not provide therapeutic value in sub-acute stroke. Consequently, to achieve therapeutics benefits from everyday walking patients should be encouraged to increase their quantity of walking and additional emphasis needs to be placed on increasing the intensity of walking. Such adaptations to walking activity can help promote and facilitate favorable recovery.
4.5 References


Table 4.1 Demographic and clinical characteristics of patients – Study 3. * denotes use of an assistive device (e.g. single point cane/rollator) throughout data collection. (HR – heart rate, CMSA – Chedoke McMaster Stroke Assessment, BBS – Berg Balance Scale)

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Gender</th>
<th>Age</th>
<th>Days Post Stroke</th>
<th>Stroke Type</th>
<th>CMSA</th>
<th>BBS</th>
<th>Resting HR</th>
<th>Preferred Gait Speed (m/s)</th>
<th>Preferred Cadence (steps/min)</th>
<th>Temporal Swing Symmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>A*</td>
<td>M</td>
<td>59</td>
<td>13</td>
<td>I</td>
<td>4</td>
<td>4</td>
<td>51</td>
<td>0.54</td>
<td>72.8</td>
<td>1.26</td>
</tr>
<tr>
<td>B*</td>
<td>F</td>
<td>31</td>
<td>28</td>
<td>I</td>
<td>3</td>
<td>4</td>
<td>32</td>
<td>0.28</td>
<td>67.2</td>
<td>1.15</td>
</tr>
<tr>
<td>C*</td>
<td>M</td>
<td>76</td>
<td>14</td>
<td>I</td>
<td>5</td>
<td>6</td>
<td>51</td>
<td>1.11</td>
<td>103.5</td>
<td>1.08</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>57</td>
<td>25</td>
<td>I</td>
<td>4</td>
<td>4</td>
<td>38</td>
<td>0.83</td>
<td>93.9</td>
<td>1.1</td>
</tr>
<tr>
<td>E*</td>
<td>M</td>
<td>38</td>
<td>68</td>
<td>I</td>
<td>5</td>
<td>5</td>
<td>41</td>
<td>1.1</td>
<td>100.6</td>
<td>0.98</td>
</tr>
<tr>
<td>F</td>
<td>M</td>
<td>54</td>
<td>46</td>
<td>I</td>
<td>5</td>
<td>5</td>
<td>49</td>
<td>0.86</td>
<td>98</td>
<td>1.03</td>
</tr>
<tr>
<td>G*</td>
<td>F</td>
<td>63</td>
<td>30</td>
<td>I</td>
<td>4</td>
<td>3</td>
<td>44</td>
<td>0.53</td>
<td>81.5</td>
<td>1.29</td>
</tr>
<tr>
<td>H*</td>
<td>F</td>
<td>47</td>
<td>32</td>
<td>I</td>
<td>3</td>
<td>4</td>
<td>33</td>
<td>0.31</td>
<td>60.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Mean   53.1 32 62.3 0.70 88.2
SD      14.2 17.9 10.7 0.33 14.4
Table 4.2 Summary of walking measures for each patient collected throughout the day.

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Total Collection time (hrs)</th>
<th>Total Walking Time (min)</th>
<th>Number of Walking Bouts</th>
<th>Duration (s)</th>
<th>Step Count</th>
<th>Mean Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7.06</td>
<td>33.3</td>
<td>46</td>
<td>43.4</td>
<td>2643</td>
<td>73.2</td>
</tr>
<tr>
<td>B</td>
<td>8.85</td>
<td>24.6</td>
<td>33</td>
<td>57.6</td>
<td>1774</td>
<td>79.2</td>
</tr>
<tr>
<td>C</td>
<td>7.86</td>
<td>31.6</td>
<td>55</td>
<td>34.5</td>
<td>3743</td>
<td>85.8</td>
</tr>
<tr>
<td>D</td>
<td>8.65</td>
<td>31.7</td>
<td>79</td>
<td>31.8</td>
<td>2201</td>
<td>78.5</td>
</tr>
<tr>
<td>E</td>
<td>8.91</td>
<td>59.3</td>
<td>91</td>
<td>45.8</td>
<td>4778</td>
<td>87.2</td>
</tr>
<tr>
<td>F</td>
<td>7.87</td>
<td>58.4</td>
<td>60</td>
<td>131.3</td>
<td>5621</td>
<td>103.6</td>
</tr>
<tr>
<td>G</td>
<td>8.41</td>
<td>78.3</td>
<td>89</td>
<td>52.4</td>
<td>5377</td>
<td>78</td>
</tr>
<tr>
<td>H</td>
<td>9.69</td>
<td>74.7</td>
<td>48</td>
<td>60.2</td>
<td>3532</td>
<td>61.6</td>
</tr>
</tbody>
</table>

Mean 8.41 48.99 62.625 57.13 3708 80.8
SD 0.8 21.2 21.3 31.6 1452 12.1
Figure 4.1 Placement of the ABLE system on a patient. A) Demonstrates the PDA data logger worn around the waist of the patient. B) Highlights a strap, worn superior to the lateral malleolus that houses the accelerometer unit.
Figure 4.2 Mean heart rate response (% HRR) versus duration of walking bout throughout collection period. Each point represents a single bout of walking performed during the collection period.
Figure 4.3 Heart rate responses (%HRR) for bouts of walking grouped into intervals. Bouts of walking are separated into intervals shown on the x-axis. Each grey line represents the mean %HRR response for each patient during walking within the specified interval, patient B (dashed line) demonstrates the highest %HRR. The dark line represents the mean %HRR across all patients.
5.0 General Discussion

The overall purpose for the present thesis was to develop a better understanding for the quantity and control of everyday walking in sub-acute stroke patients residing in a rehabilitation facility and to investigate the potential therapeutic value of everyday walking activity in patients with sub-acute stroke.

The introduction of the ABLE system to the field of ambulatory monitoring is a novel approach with respect to how data are collected and the specific measures that can be acquired. One of the main advantages of the present system is its ability to extract detailed temporal characteristics of everyday walking in patients with stroke. Previously developed measurement instruments have demonstrated the low overall quantity of ambulatory activity in stroke and other populations (e.g. step count). However, they can be limited in their use as an outcome measure in the clinical field because there is little information about the specific details of walking (e.g. temporal details regarding the frequency and duration of walking activity, temporal characteristics of individual footfalls and contacts).

To address the objectives of investigating the temporal properties and physiological responses of everyday walking in sub-acute stroke, we first sought out to develop an instrument that would allow us to evaluate such measures. Despite some concern regarding the degree of variability in gait event detection, we found that on average, the ABLE system was capable of providing individual FO and FC times. With the successful development of the ABLE system, we then sought out to assess the quantity and control of everyday ambulatory activity in patients with stroke. Although overall levels of total walking activity were low (Tudor-Locke & Bassett, 2004), they are slightly higher than previously reported values from chronic stroke patients in the community settings (Michael & Macko, 2007). An important observation was the relatively short bout durations during everyday walking, which might be explained by factors such as the state of pre-morbid functioning, current progression of recovery and even the environment. Overall, in-patient activity can be described as frequent bouts of walking, short in duration with considerable periods of inactivity dispersed throughout the day. Such characteristics may be consistent with typical walking behavior of most individuals (with or without a stroke), however it is our view that activity profiles for those engaged in active rehabilitation should be highlighted by a greater frequency of walking activity (if the individual is capable of independent walking). In our third
study, we questioned whether observed bouts of walking provided any cardiorespiratory therapeutic value to the patients; in other words, were patients able to achieve aerobic benefits by elevating and sustaining their heart rate during walking. Alternatively we sought to determine if task-related changes in cardiovascular load a potential limiting factor to walking. Patients did not often reach required intensities and did not simultaneously reach required intensities and durations for therapeutic benefit. Equally as important, patients did not often walk with excessively high heart rate responses. Thus, walking activity was not at sufficient intensity to gain any aerobic benefits nor was the walking activity leading to exceeding high workloads that might limit activity.

5.1 Limitations

The limitations of the ABLE system relate to the hardware structure and software development. The large magnitude of variability in gait event detection between the algorithm developed and the gold standard can be viewed as one of the more substantial limitations of the present study. Although our methods are acceptable for analyzing average gait data over individuals bouts of walking, future modifications to our approach is required to improve accuracy to interpret individual foot contact and foot off events. The variability observed can be attributed to several possible factors. Some of the variability is likely associated with sampling or measurement error though we suspect that this small. Despite the level of variability, it is important to note that there was no systematic bias to FC/FO detection between the footswitch and accelerometer systems. This minimized concern that we were using the wrong acceleration features to reflect FO and FC events, but it does lead us to suspect that most of the variability observed is largely due to the inaccuracy and lack of sophistication in the algorithm used feature extract FO/FC (e.g. appropriateness of the thresholds). There are other potential factors influencing the magnitude of difference scores include between-subject differences such as the type of footwear worn during collection. Future work will need to explore the influence of such factors on the characteristics of an acceleration profile of walking and the associated estimates of accelerometer-based indexes of gait characteristics.

Difficulties experienced with Bluetooth connection between the accelerometer ankle units and the PDA was unexpected, but modifications were made and the issue has been resolved in subsequent testing. Overall, the ABLE system was well received by patients with the exception of the presence of the PDA. Future development will focus on reducing the size of the common
collection point (i.e. PDA); however, if possible future system will aim to remove the PDA from the entire system, so that each independent accelerometer unit will collect synchronized data on board or transmit it wirelessly to a base station.

The current monitoring was limited to single day periods and it raises concern of the generalizability of a single day to multiple day activity profiles. Ideally, ambulatory data should have been collected over multiple consecutive days. Despite the repetitive day-to-day nature of inpatient rehab, no two days are likely alike and thus multiple day collections would have provided information that may have provide a more generalizable profile of everyday walking activity. Future studies will need to determine the benefit of multiple day evaluations and the specific utility of cumulative multiday collection for therapists. The current equipment was not design to collect continuously over consecutive days, but in the in-patient setting it is possible to put on and take off the ABLE system each day.

The studies were also limited by relatively small sample size used in both studies 2 and 3. As a result, data presented can reflect the behavior of sub-acute patient’s tested. Extending inferences to other patients in other rehabilitation facilities should be done with caution. On a related matter, another limitation affecting the generalizability of results is the large degree of heterogeneity with respect to stroke severity (Table 2.1 and 3.1) in patients tested for studies 2 and 3. Future studies will need to confirm the present observations with a larger sample of sub-acute stroke patients.

In addition, the thesis was also limited by the fact that we focused on one index, gait symmetry, as a reflection of the control of walking. The focus on gait symmetry was based on recent studies that have highlighted the utility of using gait symmetry as a measure of persisting gait control problems (Patterson et al., 2008). There are, however, alternative measures that can also reflect the level of control between the two limbs during walking. For example, comparing timing and amplitude of muscle activation in the lower limbs and quantity of vertical force produced by each limb during walking can also help reveal the status of control for walking (Chen et al., 2007; Winter, 1988). While these measures focus on different aspects of walking, they all provide a proxy measure of control of the central nervous system during walking.
5.2 Clinical Implications

The prevalence of sedentary behavior and low levels of overall ambulatory activity post-stroke have been well documented, yet very little is known about the pattern and characteristics of walking activity and its associated physiological response. The present work provides a unique and alternative approach to ambulatory monitoring that focuses on obtaining important temporal gait information that has important clinical value.

An effective application of information provided by the ABLE system would be in clinical practice (e.g. physiotherapy) when developing and maintaining treatment plans for patients. By understanding the overall quantity, bout durations, and associated physiological response of walking in each patient, clinicians would be able to develop and customize exercise prescriptions for each patient. Once an appropriate treatment plan has been made, daily temporal information can then be used to ensure that patients are performing their prescribed amounts of walking. Daily information can then be used to track walking activity to ensure that patients are engaging in their prescribed quantities of walking activity and not other non-gait specific activities (e.g. seated lower leg movement).

One of the clinical advantages of using a device like the ABLE system is that when confronted with patterns of sedentary behavior by patients, clinicians are able to remotely observe and devise treatment plans to promote activity. Addressing periods of ‘down time’ is important towards ensuring patients maximize their time during rehabilitation stay. Thus, increasing the frequency of aerobically intense activities over the course of a day may be an effective approach to rehabilitation that requires further study.

It appears that everyday walking activity engaged in by inpatients with stroke did not approach levels necessary to achieve therapeutic value to cardiorespiratory fitness/health, although it is important to note that this was only a single day snapshot. The main reason for this was likely the low levels of walking intensity. Reductions in gait velocity following stroke may limit patients potential to achieve strenuous walking activity (e.g. usually achieved by higher velocities) and as a result walking activities do not demonstrate characteristics of therapeutic activity (i.e. reduced heart rates for short durations). Besides determining the quantity of walking, ambulatory monitoring systems coupled with heart rate monitors can track the extent to which patients engage in therapeutically relevant walking activities and monitor the progression
of therapeutic walking activity over the course of rehabilitation. It is noteworthy, however that such short infrequent bouts of walking may have potentially important therapeutic benefits to sensorimotor recovery though this likely is importantly related to the quality of the walking.

An intriguing finding in study 2 was the significant differences between gait assessment measures of symmetry and ‘everyday’ walking measures of symmetry. As suspected, brief gait evaluations may not capture the true extent of gait asymmetry in patients with stroke, demonstrated by more asymmetrical walking during ‘everyday’ walking. This confirmed the notion that people maybe on their ‘best behavior’ when clinically assessed. Using a device such as the ABLE, tracking temporal gait information over an extended period of time makes it difficult for patients to mask their impairments (e.g. gait asymmetry) and provides clinicians with a more accurate estimation of for temporal gait parameters.

There is also potential for walking bout duration to be used as an outcome measure for clinical practice. Since this is one of the first studies to have examined bout duration, further study is requires to understanding the factors that govern the duration of walking bouts. More importantly, to determine what combination of bout duration and frequency of bouts should be recommended for patients residing in a rehabilitation facility.

5.3 Conclusion
The findings presented here demonstrate that an ambulatory monitoring system, such as ABLE, has the capacity to objectively evaluate the pattern of everyday walking activity in patients with stroke. We have demonstrated that patients engage in overall low levels of walking activity, primarily comprised of shout bouts with very little stress put on the cardiovascular system while walking. The use of pertinent temporal information allows clinicians to objectively examine patient gait from a distance to devise patient treatment plans that may help to augment stroke recovery.
6.0 References


