RELATIONSHIP BETWEEN CLINICAL MEASURES OF SENSORIMOTOR FUNCTION AND WALKING IN INDIVIDUALS WITH CHRONIC INCOMPLETE SPINAL CORD INJURY

by

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A thesis submitted in conformity with the requirements for the degree of Master’s of Science
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ABSTRACT

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Objectives: To describe the relationship between sensorimotor function and walking in incomplete SCI.

Methods: 25 subjects were assessed using Lower Extremity Motor (LEMS) and Pinprick (LEPS) scores, and 7 walking measures: FIM-Locomotor Score, Assistive Device Score, Walking Index for SCI, 10-metre Walk Test (10mWT), Timed Up and Go (TUG), Six-Minute Walk Test (6MWT) and Walking Mobility Scale.

Results: Walking and sensorimotor function varied between subjects. Walking measures significantly correlated with LEMS and individual leg muscles but not LEPS. 21/22 ambulatory subjects had LEMS threshold>20. Non-ambulatory subjects didn’t achieve threshold. Not all subjects completed all walking measures: 10mWT: n=19; TUG: n=14, 6MWT: n=13. Most walking measures
were significantly related. 10mWT and 6MWT were highly correlated. Subjects walking ≥ 0.95 m/s didn’t reach predicted 6MWT.

**Conclusion:** Lower extremity strength is important for walking and should be further examined with other factors in a range of subjects across different measures to fully understand these relationships.
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DEDICATION

I would like to thank my incredible husband, Petri and son, Cameron for their love, understanding, and encouragement throughout this journey.

Most of all, I would like to dedicate this thesis to my mother, Margaret Flett, who passed away in October 2006 but has always supported me in everything I have embarked upon and would be so proud to see this adventure completed.
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**GLOSSARY OF TERMS**

**Determinants of Walking:** Factors, that at a given point in time, allow an individual to walk normally, navigate safely and efficiently in such a way that when the factor becomes insufficient it prevents or limits walking.

**Predictors of Walking:** Factors that can predict or determine the likelihood of walking in the future.

**Walking Ability:** Defined as the ability to step reciprocally while maintaining control of the process in order to meet the internal and external challenges of one’s environment with efficiency.
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LIST OF ABBREVIATIONS

6MWT – Six-minute Walk Test
10mWT – Ten-meter Walk Test
AFO – Ankle Foot Orthosis
ASIA – American Spinal Injury Association
AIS – ASIA Impairment Classification
ANOVA – Analysis of Variance
BWSTT – Body Weight Supported Treadmill Training
CPA – Canadian Paraplegic Association
DLEMS – Distal Lower Extremity Motor Score
EM-SCI – European Multicenter Study of Human Spinal Cord Injury
FES – Functional Electrical Stimulation
FIM – Functional Independence Measure
FIM-L – Functional Independence Measure – Locomotor Score
ICCP – International Campaign for the Cure of Spinal Cord Injury Paralysis
ISCI – International Standards for the Neurological Classification of SCI
KAFO – Knee Ankle Foot Orthosis
LAf – Least Affected Limb
LE AD – Lower Extremity Assistive Device Score
LEMS – Lower Extremity Motor Score
LEPS – Lower Extremity Pinprick Score
m – Meters
M – Mean
MAf – Most affected limb
MA – Motor asymmetry
m/s – Meters/second
N – Not able to stand and initiate steps
NL – Neurological level
n/t – Not tested
PLEMS – Proximal Lower Extremity Motor Score
RGO – Reciprocating Gait Orthosis
s – Seconds
S – Able to stand and initiate at least 3 steps with ≤ moderate assistance
SCI - Spinal Cord Injury
SCI-FAI – Spinal Cord Injury Functional Ambulation Inventory
SCILT – Spinal Cord Injury Locomotor Trial
SCIRE – Spinal Cord Injury Rehabilitation Evidence
SD – Standard Deviation
Total AD – Total Assistive Device Score
TUG – Timed Up and Go Test
UE AD – Upper Extremity Assistive Device Score
W – Able to walk at least 10 meters with ≤ moderate assistance
WISCI-II – Walking Index for Spinal Cord Injury – Version Two
WMS – Walking Mobility Scale
CHAPTER 1: General Introduction

A spinal cord injury (SCI) is considered to be one of the most devastating conditions an individual can experience impacting on all aspects of their life. Not only does it affect the individual physically, emotionally, and financially, a SCI has a significant impact on a person’s family as well as society at large. It has been estimated that the incidence of SCI is approximately 35 people per million of the population in Canada (Canadian Paraplegic Association (CPA), 2004). This translates to over one thousand new spinal cord injuries each year. In comparison to heart disease or osteoarthritis, SCI can be considered a relatively low prevalence condition with approximately 41,000 in Canadians living with SCI (CPA, 2004). Despite much smaller numbers, the lifetime financial cost can be significant ranging from $1.25 million for an individual with paraplegia up to $25 million for an individual with a high cervical SCI (Rick Hansen Foundation, 2008).

Studies have revealed a promising trend towards an increase in the proportion of spinal cord injuries that are incomplete in nature (DeVivo, 1992, Burney, 1993). Incomplete SCI is defined as the partial preservation of sensory and/or motor function in the lowest sacral segment (Marino, 2003). Incomplete SCI now accounts for over half of all spinal cord injuries (Go, 1995, Wyndaele, 2006). This finding suggests that regaining the ability to walk is becoming a realistic possibility for a growing number of individuals with SCI. It has been reported that 46 – 85% of patients will recover some capacity to walk following an incomplete SCI (Burns, 1997, Waters, 1994a, Waters, 1994b) however the extent of walking ability is difficult to predict. Part of the difficulty in predicting the extent of walking ability is due to the complexity of walking as well as a lack of consensus on a definition of “able to walk” or “functional walking”. A review of the SCI literature found over 10 different definitions for “able to walk” ranging from being able to walk 10 metres up to 200 metres, with assistance or without assistance, and within the home or
in the community (Burns, 1997, Crozier, 1991, Curt, 1998, Daverat, 1988, Hussey, 1973, Kay, 2007, Oleson, 2005, Penrod, 1990, Stauffer, 1978, Waters, 1994c). In order to accurately describe walking ability within a heterogeneous population such as incomplete SCI, it is important to consider walking within a theoretical framework and ensure that walking ability is measured both objectively and comprehensively.

The development of study objectives and methodology for the present study was guided by a theoretical framework for walking in SCI which is summarized in Figure 1. Central to this theoretical framework are the concepts of determinants of walking, overall community mobility, and measurement and evaluation. Determinants of walking are factors that allow an individual to walk normally, navigate safely and efficiently in such a way that when the factor becomes insufficient it prevents or limits walking (Nadeau, 2001, Barbeau, 2003). The relative importance of individual determinants will vary depending upon the patient population (Barbeau, 2006). For example, in SCI, the majority of walking determinants that have been established to date relate to injury severity and specifically the extent of lower extremity motor function. Understanding how specific determinants of walking influence an individual’s ability to walk in their community is critical in clinical decision making and the development of new therapeutic interventions. It is therefore essential to differentiate between: 1) the act of walking which incorporates upright stance and propulsion or stepping but is not necessarily functional and 2) community mobility which integrates all of the components of walking as well as the external demands that must be met in order to be independently mobile in the community. The theoretical framework presented in Figure 1 combines the physical determinants of gait described by Barbeau et al. (2006) with a conceptual model for community mobility adapted from Patla and Shumway-Cook (1999) with the overarching concepts of measurement and evaluation.
Figure 1 illustrates the important link between the determinants of gait and overall community mobility. Patla’s model for community mobility (1999) emphasizes the importance of considering the key environmental dimensions or external demands that must be met in order to be independent in the community. Although a detailed review of these dimensions is beyond the scope of this paper, the key environmental dimensions for community walking are as follows: minimum walking distance, time constraints, ambient conditions, terrain characteristics, external physical load, attentional demands, postural transitions, and traffic level. The focus of the majority of SCI walking literature to date has been in the areas of distance and time (Lam, 2008) however attentional demands (Lajoie, 1999), postural transitions, specifically gait initiation (Chang, 2004), and terrain characteristics (Lapointe, 2001) have also been examined. A SCI results in both sensory and motor impairments and can impact the upper and lower extremities as well as the trunk. Given the complex nature of SCI, it is highly likely that other dimensions of
community mobility such as the postural transition from sit-to-stand is affected following a SCI and need to be considered when measuring and understanding walking ability. Consideration of a broad range of walking determinants as well as the multiple components of community mobility will enable researchers and clinicians to develop and evaluate therapeutic intervention for walking within a broader and more meaningful context.

Understanding the clinical factors which influence walking ability is essential for the delivery of optimal rehabilitation. In addition to informing the prognosis for walking, knowledge of the clinical factors that relate to walking can enable the creation of individualized rehabilitation strategies, support the development of new, targeted rehabilitation interventions, and finally facilitate the design of future clinical trials.

Significant progress has recently been made in the area of outcome measures for walking in SCI. Several walking measures have been validated or developed specifically for use in SCI which enables clinicians and researchers to more comprehensively and objectively measure walking ability. Both the SCI Rehabilitation Evidence (SCIRE) working group (Lam, 2008) and the International Collaboration for the Cure of SCI Paralysis (ICCP) (Steeves, 2007) have recently completed systematic reviews of existing SCI walking measures and concluded that no one measure is sufficient but recommend using multiple measures including both timed measures such as the Ten-metre Walk Test (10mWT) (van Hedel, 2005) as well as categorical measures such as the Walking Index for Spinal Cord Injury-Version Two (WISCI-II) (Appendix 1) (Ditunno, 2001). The SCI Locomotor Trial (SCILT), a large multicentre randomized clinical trial of locomotor training in incomplete SCI, adopted the most comprehensive group of walking measures to date for a clinical trial. The primary outcome measures were walking speed and the Functional Independence Measure- Locomotor Score (FIM-L) and the secondary outcome measures were the WISCI-II, Six-minute Walk Test (6MWT), and Berg Balance Scale (Dobkin,
2003). Other clinical trials and observational studies have also utilized more than one measure. To date, however, walking ability in incomplete SCI has not been comprehensively described using a broad range of walking measures across different levels of walking ability nor have the clinical factors related to walking ability been examined with respect to multiple components of walking ability.

The overall study objective of the present work was to describe the relationship between clinical measures of sensorimotor function and different constructs of walking in chronic, motor-incomplete spinal cord injury. The research objectives, results, and discussion of the overall study have been divided into two manuscripts which are the contents of chapters three and four.

**Research Objectives:**

**Manuscript 1**

To describe the extent of sensorimotor function and walking ability in a sample of individuals with chronic, incomplete SCI and the relationship between lower extremity sensorimotor function and current clinical walking measures in SCI.

**Manuscript 2**

1. To examine how current SCI walking measures describe walking ability in a cross-section of individuals with chronic motor-incomplete SCI.
2. To understand the inter-relationships SCI walking measures
3. To determine whether the 6MWT can provide meaningful information beyond the 10mWT in chronic SCI
CHAPTER 2: Literature Review

2.1 International Standards for the Neurological Classification of SCI (ISCSCI) as a measure of injury severity and sensorimotor function

The International Standards for the Neurological Classification of SCI (ISCSCI) is widely used for the classification and assessment of individuals with traumatic SCI. The impetus for the development of the International Standards was to create a standard and consistent approach to describing SCI across different professions, countries, and to enable comparison between different clinical trials.

The ISCSCI examination is comprised of an assessment of sensory and motor function to determine both a neurological level (NL) as well as the American Spinal Injury Association Impairment Scale (AIS) (Appendix 2). The sensory component consists of light touch appreciation and pinprick discrimination testing of twenty-eight key sensory points using a three-point scale (0 = absent, 1 = impaired, 2 = normal). In addition to light touch and pinprick testing, the assessment of joint position sense and deep pressure are included in the ISCSCI as optional items. Sensory scores are used to determine a total sensory score as well as a sensory level which is defined as the most caudal level with normal sensory function. The motor examination consists of manual muscle testing of 5 key upper extremity which correspond to the C5 – T1 spinal cord roots and five key lower extremity muscle groups which correspond to the L2 – S1 spinal cord roots. Motor function is scored using a 5-point scale for a total motor score out of 100. In order to provide more accurately reflect the extent of impairments, it has been recommended that the total motor score be divided into an upper extremity motor score (UEMS) and lower extremity motor score (LEMS) (Marino and Graves, 2004). Motor scores are also used to determine a motor level which is defined as the most caudal level with at least a grade three strength provided the key muscle representing the segment above has normal strength.
(grade 5). Due to the difficulty in easily and accurately testing trunk muscle function at individual segments, the ISCSCI does not include motor testing of any axial muscle, relying on the sensory scores at these levels to determine NL.

The motor and sensory levels are used to establish a NL which is the lowest spinal cord segment with normal sensory and motor function. The other important component of the ISCSCI examination is the ASIA Impairment Scale (AIS) which provides an indication of injury severity or the completeness of the SCI. The determination of the completeness of an injury is based on the presence of sacral sensory or motor function (“sacral sparing”). A complete SCI is defined as the absence of sensory and motor function in the lowest sacral segment. Incomplete SCI is defined as the partial preservation of sensory and/or motor function in the lowest sacral segment (S4-5). The AIS is compromised of 5 categories as follows: AIS A - complete SCI, AIS B - sensory incomplete SCI, AIS C - motor incomplete, AIS D – motor incomplete, and AIS E – normal. Although AIS C and D are both defined as “motor incomplete”, they can be differentiated by the extent of motor recovery below the NL. Individuals classified as AIS C have sacral sparing and preserved motor function below the NL however the majority (> 50%) of key muscles have strength of less than grade three whereas in the case of AIS D individuals at least half of the muscle groups below the NL have at least anti-gravity strength. The inter-rater and intra-rater reliability of the summed scores for pinprick, light touch, and motor function have all been shown to be excellent (>0.96). (Marino, 2008, Savic, 2007, Cohen, 1996)
2.2 Factors associated with walking ability following SCI

2.2.1 Predictors of walking following SCI

One of the most common questions patients and their families ask following a SCI is whether they will be able to walk again. Determining the prognosis for walking is critical for setting expectations, guiding treatment planning, and determining equipment and other discharge needs.

Injury severity based on the AIS has been shown to be one of most useful early predictors of walking following a SCI. It has been well-established that individuals with complete SCI (AIS A) rarely walk (Maynard, 1979, Waters, 1992, Waters, 1993) and if they do so, they rely on cumbersome orthoses, exert significantly more energy and thus often do not continue to walk long-term (Cerny, 1980, Hussey, 1973).

Individuals with sensory-incomplete SCI (AIS B) present with a better prognosis for walking than those with a complete SCI. Studies have shown that 20 - 50% of individuals initially classified as AIS B will recover the ability to walk by one year (Stover, 1986, Crozier, 1991, Maynard, 1979, Oleson, 2005, Katoh, 1995). In one of the earliest prognosis studies, Maynard et al. (1979) established the superiority of the 72-hour neurological examination over an immediate post-injury examination. The authors found that only 47% of sensory incomplete patients were able to walk at one-year post SCI whereas 87% of motor incomplete patients (AIS C and D) were able to do so. For sensory-incomplete injuries (AIS B), the nature of sensory sparing is particularly important. In a retrospective study, the presence of pinprick sensation in addition to light touch sensation in AIS B patients was associated with a significantly better prognosis for walking at one year (Crozier, 1991). A secondary analysis of the Sygen © (GM1-ganglioside) trial has been the largest study (n=131) to date examining individuals with AIS B injuries. In this study, Oleson and colleagues (2005) found that sacral (S3-5) pinprick
preservation at 4 weeks post-injury and baseline lower extremity pinprick preservation were both associated with an improved prognosis for walking. Forty percent of individuals with lower extremity pinprick preservation were functional ambulators at one year compared to 16% of individuals with only light touch preservation.

The presence of motor function below the neurological level early post-injury significantly increases the chances of walking. Based on the 72-hour ISCSCI examination, 80% of individuals with tetraplegia classified as AIS C and 100% of AIS D patients were able to walk at discharge from rehabilitation (Burns, 1997). The AIS at rehabilitation admission has also been shown to predict walking status at discharge. Fifteen percent of AIS B, 28–40% of AIS C, and 67–75% of AIS D patients were able to walk at discharge (Dobkin, 2003, Kay, 2007).

Early lower extremity motor function has also been found to be a strong predictor of walking (Waters, 1994a, Waters, 1994b, Curt, 1997, Curt, 1998). In his recovery studies, Waters (1994a, b) found that the one-month LEMS closely correlated with walking status at one year. In fact, 87% of incomplete tetraplegics and 100% of incomplete paraplegics who had a LEMS of at least 10 by one month post-injury were community ambulators at one year. This study also found that individuals with incomplete paraplegia who initially had at least grade two strength in the hip flexor or knee extensor of one leg had sufficient motor recovery in other musculature to enable community walking by one year. Curt and colleagues (1997, 1998) also examined the correlations of admission LEMS, somatosensory-evoked potentials and motor-evoked potentials with ambulatory capacity at six months post-SCI. The results showed that LEMS in addition to evoked-potential recordings were predictive of ambulatory capacity based on a 4-point ordinal scale. Crozier (1992) also demonstrated that achieving at least grade three muscle strength in the knee extensors within 2 months after a SCI was predictive of functional ambulation at 6 months post-injury. A large, retrospective study of SCI patients admitted to rehabilitation over a 10-year
period in Japan also linked the rate of lower extremity recovery to the degree of independent ambulation (Suyama, 1999). The above literature clearly demonstrates the predictive ability of initial injury severity as measured by AIS and lower extremity motor function. Unfortunately, the methods used to measure walking outcomes vary across these studies and often provide little insight into the range of walking outcomes and the functionality of walking.

The specific neurological level of injury has not been shown to predict walking ability (Kay, 2007) however distinctions have been found between individuals with paraplegia and tetraplegia. For equal walking function, patients with tetraplegia required greater LEMS compared to individuals with paraplegia (Wirz, 2006). Higher ambulation rates were also found at 1 and 2-year follow-up in incomplete paraplegics versus incomplete tetraplegics (76% vs. 46%) (Waters, 1994a, b). This may be attributed to greater trunk muscle impairment and less ability to rely on ambulation aids in individuals with tetraplegia.

Age has also been shown to be a factor in walking prognosis. In individuals with Central Cord Syndrome, 97% of individuals under age 50 were able to walk at discharge compared to only 41% over of individuals over age 50 (Penrod, 1990). In individuals with AIS C incomplete tetraplegia, those over age 50 were significantly less likely to recover walking (42% vs. 91%) (Burns, 1997). Kay (2007) did not find the same age effect with AIS C patients however found that individuals over age 50 with AIS D SCI were less likely to walk at discharge (55% vs. 79%).

Over the last 10-15 years, there has been a tremendous growth in the number of studies examining the effects of new therapeutic interventions such as body-weight support treadmill training (BWSTT), functional electrical stimulation (FES), robotic-assisted training on the recovery of locomotion following a SCI. The underlying theoretical rationale for these interventions is grounded in the importance of appropriate afferent input and sensory integration to facilitate neuroplasticity and the recovery of walking. To date however, there has been little
research, which directly examines the relationship between sensory function and walking ability in this population. Aside from the studies of individuals with sensory incomplete SCI described above, only a few studies have examined this relationship. Curt (1998) studied the significance of motor-evoked potentials and ISCSCI scores to functional outcomes and found significant correlations ($\rho = 0.53 - 0.74$) between ambulatory capacity and ISCSCI sensory scores in both acute and chronic SCI. Early work by Hussey (1973) involving 164 patients admitted to the Ranchos Los Amigos SCI service suggested the importance of proprioception for ambulation following a SCI. Of the patients who were household or community ambulators, 95% and 92% respectively had normal proprioception in their lower extremity joints whereas individuals in the exercise only or non-ambulatory groups had more impaired lower extremity proprioception. Although intuitively it seems highly plausible that proprioception is related to walking ability following a SCI, this relationship has not been further validated.

### 2.2.2 Determinants of walking in SCI

In SCI, lower extremity motor function is not only an important predictor of walking outcome but also a major determinant or correlate of walking status at a given point in time. Both composite and individual muscle strength scores have been shown to correlate with walking status in individuals with SCI. Several authors have demonstrated significant relationships between LEMS and walking status (Waters 1994c, Scivoletto, 2008, Kim, 2004).

Waters et al. (1994c) compared LEMS with measures of gait performance and energy expenditure in 36 subjects with SCI who were at least 6 months post-injury and were able to walk independently for at least 5 minutes. The sample included 20 individuals with motor-incomplete paraplegia, 12 with motor-incomplete tetraplegia and 4 with complete paraplegia. The authors found that LEMS strongly correlated with the rate of oxygen consumption, peak
axial load exerted through upper extremity assistive devices, walking speed, and cadence. In addition, they demonstrated that a LEMS of greater than 30 was associated with community ambulation whereas subjects with a score below 20 were limited ambulators with slower walking speeds and higher heart rates.

A more recent Canadian study of 22 chronic incomplete SCI subjects examined the relationship between lower extremity muscle strength and functional walking measures such as the 10-metre walk test, 6-minute walk test, and ambulatory capacity (Kim, 2004). The authors found that LEMS was highly related ($r > 0.70$) to all three walking measures. They also demonstrated that proximal muscle strength, particularly of the less affected side, was an important determinant of walking ability. Specifically, the strength of the less affected hip flexors accounted for 50% of the variance in 10mWT and 6MWT whereas the strength of the less affected hip extensors accounted for 64% of ambulatory capacity.

In a study of 65 individuals with chronic, incomplete SCI, Scivoletto and colleagues (2008) examined the influence of several clinical factors such as LEMS and UEMS, pinprick and light touch sensory scores, balance, spasticity, and pain as well as non-clinical factors such as age, gender, and weight on walking ability as measured by the 10mWT, 6MWT, TUG, and WISCI-II. They found that LEMS, UEMS, proximal LEMS, Berg Balance score, and age were all significantly related to walking ability.

In normal gait and stroke literature (Michael, 2005), the importance of postural control for walking has been identified. In the Scivoletto study described above the Berg Balance Scale was found to be the only significant predictor of walking level (WISCI-II) as well as a strong predictor of 6-minute walk distance. In fact, balance had higher correlations to all walking tests than LEMS. Beyond this study, there has been little research in SCI to support the importance of postural control or trunk muscle function for walking in SCI. This is likely due to the omission
of trunk muscle function from the ISCSCI examination and the complexity of measuring these muscles particularly in upright stance.

2.3 Clinical measurement of walking in SCI

Meaningful and accurate measurement of walking outcomes is essential for both clinical practice and research trials. Rehabilitation measures are considered to have three general purposes; to evaluate change, to predict outcomes, and to discriminate between groups (Cole, 1994). Given the intense focus of SCI research on recovery through pharmalogical, surgical, or rehabilitation interventions, it is important for outcomes measures to be psychometrically sound, clinically meaningful, and capable of detecting change in the desired outcome.

Significant advances have been made in the last decade in the area of walking measures in SCI. A review of past SCI studies highlights the progress gained in walking measurement. In early observational studies, which examined the incidence and predictors of walking in SCI, walking ability was described dichotomously. For example, in his large studies examining the recovery of motor and sensory function, Waters and colleagues (1994) described walking outcomes based on whether subjects were “community ambulators” which was defined as being “able to get themselves out of a wheelchair or bed and walk a reasonable distance both in and out of the home unassisted by another person. They may use crutches or braces and a wheelchair for exceptionally long distances”. Penrod (1990) and Crozier (1991) both measured walking status as whether or not subjects were able to ambulate independently over set distances of 50 feet and 200 feet respectively. In contrast, early experimental studies investigated in great detail the specific physiologic aspects of walking performance. For example, in the original body weight support treadmill training (BWSTT) study, Visintin and Barbeau (1989) examined the influence of a single session of BWSTT on electromyographic and kinematic variables. Other studies have
examined the physiological cost of walking (Granat, 1993) and interlimb coordination (Field-Fote, 2002) in subjects with incomplete SCI. While electromyographic, kinematic, kinetic, and metabolic measures can provide insight into specific gait deficits and help to determine mechanisms underlying the effects of the interventions, these instruments are often not readily available in the clinical setting. Furthermore, laboratory measures do not necessarily describe what is occurring at the level of the individual in their environment and the extent of their walking ability.

In more recent clinical trials of locomotion in SCI, there appears to be a recognition of the importance of using validated measures and evaluating the function of walking in its entirety. The SCIRE Working Group (Lam, 2008) and the ICCP (Steeves, 2007) have recently completed reviews of SCI walking outcome measures. Both the ICCP panel as well as other authors (Ditunno, 2007, Schmidt-Read, 2008) have recommended that a combination of walking measures be used rather than one single measure. For example, in the SCILT, the largest multicentre randomized clinical trial in SCI to date, a comprehensive set of outcomes measures including four validated walking measures (FIM-Locomotor Score, 10mWT, 6MWT, and the WISCI-II) was utilized. This progress is important as it demonstrates an acknowledgement of the complexity of walking and that different interventions may influence different aspects of walking ability.

SCI walking measures can be classified into timed and categorical measures (Lam, 2008). Timed walking measures are comprised of either a timed walk over a pre-determined distance which can be used to calculate walking speed or a distance walked over a pre-determined time. Categorical walking measures involve the use of ordinal scales to distinguish between different levels of walking ability. Categorical walking measures have the advantage of capturing both walkers and non-walkers and the transition between these states. In addition, unlike timed
measures, they do not have a minimal distance or time required to complete the test. It is however important to acknowledge that the intervals between categories may not be equal.

Timed walking speed is likely the most well-known and commonly used measure of walking ability. In fact, walking speed has been described as the most valid means of assessing functional walking performance and considered by some to be the criterion standard of walking ability in SCI (Field-Fote, 2001, van Hedel, 2008). Various methodologies have been used in the literature to determine walking speed. Performance is timed over a pre-determined distance with the outcome typically reported as a temporal-distance measure (m/s). An acceleration and deceleration period of up to 3 metres is usually provided and subjects are permitted to use their preferred assistive devices. Standardized instructions are provided to the individual asking them to walk at a specified pace (e.g. “comfortable”, “preferred”, “maximum”) and a digital stopwatch is typically used though electronic timing methods can also be employed (Finch, 2002).

The 10mWT has been the most widely used walking measure in SCI clinical trials and practice (Schmidt Read, 2008) and recently has been cited as best tool to assess walking capacity in SCI (van Hedel, 2008). Though the psychometric properties of this test have long been established in comparable populations (Wade, 1987, Holden, 1984), only recently has this been investigated in SCI. In a study of 22 subjects with incomplete SCI, van Hedel et al. (2005) found the 10mWT to have excellent intra- and inter-rater reliability ($r = 0.983$ & $r = 0.974$ respectively). Furthermore, when examining the validity in 75 subjects, the 10mWT was found to have excellent correlations with the Timed Up & Go test (TUG) ($r = 0.89$), and 6 Minute Walk Test (6MWT) ($\rho = -0.95$). The 10mWT was also shown to have a good significant correlation with the WISCI-II ($\rho = -.68$). It is important to note in this study that the units of measure were time (in seconds) and not velocity, which accounts for the negative correlations with both the WISCI-II and 6MWT. In the European Multicentre Study of Human SCI (EM-SCI), 22 subjects
with incomplete SCI were examined at 3, 6, and 12 months post-SCI. The authors found the 10mWT to be responsive to improvements in walking capacity throughout all time intervals (van Hedel, 2006). In another study utilizing data from EM-SCI, van Hedel (2007) found that the preferred walking speed of subjects with incomplete SCI was a significantly higher percentage of their maximum walking speed than normal subjects (74% vs. 59%). The authors concluded that preferred walking speed may only partially reflect community participation and that the percentage of preferred speed divided by maximum walking speed is indicative of the remaining capacity of subjects to increase speed towards maximum which may better reflect the ability to meet community challenges.

Other distances have also been utilized to calculate walking speed in the SCI literature. (Postans, 2004, Kim, 2004, Dobkin, 2003, Field-Fote, 2001) In the SCILT, Dobkin et al. (2003) used walking speed over 50 feet (15.2 metres) as the primary outcome for subjects classified as AIS D. Two trials were performed with a 5-minute rest period in between. Finally, Field-Fote and colleagues (2001) calculated walking speed over a two-minute time period. In this test, subjects were instructed that they would be walking for 2 minutes so to walk at a fast but comfortable pace. The authors felt that this longer time frame reflected a more functional time period to calculate walking speed.

Though originally developed as a measure of basic functional mobility in the frail elderly (Podsiadlo, 1991), the Timed Up and Go Test (TUG) is now used as a measure of functional walking performance. The TUG measures the timed performance of rising from a chair, initiating walking, walking 3 metres, turning, and walking back to the chair to sit down. Both the instructions to the individual as well as the test administration are standardized (Finch, 2002). In conjunction with other measures, the TUG has undergone reliability and validity testing in SCI (van Hedel, 2005). It was shown to have excellent intra- and inter-rater reliability ($r = .979,$
The TUG was found to highly correlate with the 6MWT ($\rho = -0.88$) and the 10mWT as previously discussed. The TUG was also shown to have a good correlation with the WISCI II ($\rho = -0.76$). The TUG is currently being used as part of the EM-SCI database. In a recent publication from this database, van Hedel et al. (2008) reviewed the current status of four walking measures used in SCI: the 10mWT, 6MWT, TUG, and WISCI-II. They also examined the relationship between the 10mWT and the TUG which had yet to be studied. The authors found that the two measures were highly correlated at all five time points (2 weeks, 1, 3, 6, 12 months) ($\rho > 0.80$) however the relationship changed over time. Sciveletto (2008) examined the relationship between the TUG as well as other walking measures and several clinical factors. The results indicated significant correlations between the TUG and Berg Balance Scale ($r=-0.628$), Modified Ashworth Scale (MAS) for spasticity ($\rho = 0.283$), Total Motor Score ($r=0.266$), and the Proximal LEMS (PLEMS) ($r=-0.397$). Further stepwise regression analysis found spasticity as measured by the MAS ($P=0.000$) and PLEMS ($P=0.001$) were the best predictors of the TUG. Although the TUG has yet to be cited in any clinical trials in SCI, it is currently being utilized in the FES-assisted walking for the secondary complications of SCI trial in Toronto of which this thesis is part of.

The six-minute walk test (6MWT) is another walking test that has been increasingly used in the SCI literature. It was originally developed as a measure of exercise tolerance in individuals with respiratory disease (Butland et al., 1982). The 6MWT is a performance-based test in which subjects are asked to walk as far as they can in 6 minutes with distance walked being measured. Subjects are permitted to rest if they require and administration is standardized. The 6MWT has been utilized as a measure of walking endurance in several walking studies in SCI over the last decade (Dobkin, 2003, Hesse, 2004, Kim, 2004, Postans, 2004, vanHedel 2005, 2006, 2007). The psychometric properties of the 6MWT have been established in SCI by van
Hedel et al. (2005). The 6MWT was shown to have excellent intra- and inter-rater reliability ($r = 0.981$ & $r = 0.970$). As previously discussed, it was also found to significantly correlate to both the TUG and 10mWT. In addition, a moderate to good significant correlation was found with the WISCI II ($\rho = 0.60$). Consistent with the 10mWT, van Hedel (2006) found the 6MWT to be responsive to change over time in subjects from the EM-SCI database. More recently, several authors have questioned the value of the 6MWT in addition to the 10mWT. In particular, very high correlations have been consistently found between the two measures (> 0.95) (Kim, 2004, van Hedel 2005, 2007, Barbeau, 2007) however these high correlations alone should not imply redundancy (van Hedel, 2007). Barbeau (2007) further examined the relationship between the short distance walking speed (15.2 m) and 6MWT in subjects participating in the SCILT and found that the results were comparable between the measures. More specifically, the mean speeds for the 15.2 m and 6MWT were not significantly different at 3 and 6 months but the mean 15.2 m walking speed was faster at 12 months post-injury. In addition, the authors found that at each time point, walking speeds were similar between the tests until a threshold speed of approximately 0.8 – 1.0 m/s was reached at which point subjects walked 14 - 24% faster during the 15.2 m test. Van Hedel (2007) also found that walking speed was not significantly different between the 10mWT and 6MWT throughout the first 6 months of recovery following SCI and therefore concluded that the 2 measures provide comparable information in individuals with SCI. The authors did however acknowledge that a selection bias may exist in the administration of the 6MWT such that therapists may not perform this test in subjects with poor walking ability and therefore would not have been included in the analysis.

The Walking Index for Spinal Cord Injury (WISCI) is the first new walking measure to be developed specifically for SCI. Created by Ditunno and colleagues (2000), the WISCI was originally developed as a 19-level ordinal scale and considers the degree of physical assistance as
well as upper and lower extremity assistive device use during a 10-metre walk. The purpose in developing the WISCI was to create a simple but precise walking measure for use in clinical trials. The ranking of items on the scale was achieved by consensus from a group of international experts, which the authors felt demonstrated face validity of the scale. The concurrent validity was also established as the WISCI was shown to significantly correlate with FIM locomotor scores ($\rho = 0.765$). In this same original study (Ditunno, 2000), the authors investigated the inter-rater reliability of the WISCI through the use of 40 videotape clips of subjects walking. Although a 100% agreement was found between raters in terms of the scoring, it can be questioned whether this was true test of the reliability of the measure. It is not surprising that all of the raters (who were clinicians or researchers working in SCI) consistently obtained the same scores when rating the assistive devices used and the degree of physical assistance provided. This study did not however determine the reliability of determining the types of assistive devices or the degree of physical assistance that individual subjects would require. It is highly likely that this aspect of scoring would provide a much greater degree of subjectivity and variability amongst raters as this determination may be based on a number of factors in addition to walking ability such as clinical experience, treatment philosophy, patient preference and the prescription and accessibility of different assistive devices.

In 2001, the WISCI scaling was revised to include two additional levels resulting in a 21-level ordinal scale called the WISCI-II (Ditunno, 2001). In this same paper, the authors also indicated that the WISCI-II was responsive to change. In their retrospective analysis of 103 patients, the authors found that the AIS classification at initial assessment and at maximum recovery of walking were significantly correlated with WISCI-II scores. ($P < 0.03$ & $P < 0.001$). In addition, initial AIS were correlated with final WISCI levels ($P < 0.001$).
The WISCI-II has recently been adopted in a number of studies. For example, the WISCI-II was included as a secondary outcome measure in the SCILT (Dobkin, 2003) as well as the EM-SCI database (Curt, 2004). The ICCP panel has also recommended the use of the WISCI-II as a sensitive and precise measure for the rating of functional walking and advised that it be used in combination with a timed measure such as the 10mWT. The WISCI-II was also used as the “gold standard” in establishing the validity of 3 walk tests as previously mentioned (van Hedel, 2005). Although the overall correlations in this study were significant between the WISCI-II and the three timed measures (10mWT, 6MWT, and TUG), the authors found that in individuals with poor walking ability (WISCI-II levels 0-10), the WISCI-II did not correlate significantly with any of the timed measures ($\rho = 0.20–0.24$). In this study, van Hedel and colleagues also question whether the ranking of items in the WISCI was appropriate. For example, they felt that achieving independent walking even if aids or orthoses were used should be valued more than walking without an aid but with physical assistance.

Further investigations into the psychometric properties of the WISCI-II have also been completed. Morganti (2005) compared the WISCI-II to a number of other measures. In their retrospective chart review, moderate to good significant correlations were found with the Barthel Index ($r=0.67$), the Rivermead Mobility Index ($r=0.67$), FIM ($r=0.70$) and a strong significant correlation with the SCI Independence Measure (SCIM) ($r=0.90$). In addition, consistent with other studies involving the WISCI-II, the authors found that the majority (79%) of subjects’ scores fell within three WISCI-II levels, which involved the use of no braces. This finding highlights the concern raised by van Hedel (2005) related to the appropriateness of scoring of the WISCI-II. There are a few potential explanations for this trend towards 3 WISCI II levels. Firstly, funding constraints and time requirements to fabricate some custom braces may limit their application. Secondly, recent literature related to recovery following a SCI seems to more
heavily emphasize FES & BWSTT and de-emphasizes the use of orthoses (Barbeau, 1999, Basso, 2000). It is also noteworthy with the WISCI-II scoring that an individual with a complete SCI can still achieve a score of 9/20 (“Ambulates with a walker & braces, no physical assistance”). For these reasons, the WISCI-II must be used cautiously in recovery studies. It is also possible for subjects to utilize several different combinations of assistive devices and physical assistance. Kim et al. (2007) examined the differences between self-selected and maximum walking capacity as measured by WISCI-II in individuals with chronic SCI. They found that although individuals were capable of walking at multiple levels, they were more efficient at their self-selected WISCI-II level in terms of walking speed, Physiological Cost Index, and Total Heart Beat Index. Ditunno has also recently examined both the concurrent and predictive validity of the WISCI-II (2007) as well as the construct validity in a European and US clinical population (2008). In the first study, the authors concluded that the WISCI-II demonstrated construct validity. Highly significant correlations were found between the WISCI-II and other measures used in the SCILT: LEMS (r=.85), Berg Balance Scale (r=.90), FIM Locomotor Scale (r=.89), 15.2 m walk test (r=0.85), and 6MWT (r=.79). The predictive validity of the WISCI-II was also shown by significant correlations between change scores between the WISCI-II and LEMS, Berg Balance, and FIM-Locomotor Score. More specifically, Ditunno (2007) concluded that the baseline LEMS was the best predictor of 12 month WISCI-II score. In the 2008 study, the authors confirmed the significant relationship between LEMS and WISCI-II at both initial and final assessment however they also identified differences in practice between European and US centres. In particular, the results revealed greater usage of parallel bars in European centres as well as more frequent use of lower extremity braces in US facilities. This finding warrants consideration in the design of clinical trials in order to account for such regional variations in practice.
The SCI Functional Ambulation Inventory (SCI-FAI) is another walking measure designed specifically for this population (Field-Fote et al., 2001). The SCI-FAI incorporates both timed and categorical walking measures. Although this measure has not received the same degree of interest in the literature as the WISCI-II, the SCI-FAI has a number of clinically relevant components. In contrast to the WISCI-II, this measure is considered an “observational gait assessment instrument” and assesses several aspects of walking performance. The SCI-FAI was developed through consultation with physical therapists experienced in SCI rehabilitation that identified the features of walking which were considered critical in this population. Based on this information, the SCI-FAI was created consisting of 3 domains: 1) Parameters (weight shift, foot contact, step width, rhythm, height, & length) using a 2- or 3-point ordinal rating for each limb for a total score of 20; 2) Assistive devices which scored both the upper extremity balance and weight bearing devices used as well as the lower extremity assistive devices used. An Upper & Lower Extremity Assistive Device score were generated as well as a Total Assistive Device score (/14); and finally 3) Temporal/distance measures which included a 2-minute walk test to calculate walking speed and a Walking Mobility Scale (WMS) which reflects the typical walking practice or the extent of community walking. The WMS was based on categories described by Perry et al. (1995). Kim et al. (2004) have also used this classification system as a means of describing “ambulatory capacity” The WMS is based on a subject’s reports regarding the extent of their walking in the home and community and provides a more global rating of overall walking participation.

Although the SCI-FAI has not been utilized in any clinical trials, Field-Fote and colleagues examined its psychometric properties using a sample of 22 subjects with chronic incomplete SCI. In terms of inter-rater reliability, there was a 100% agreement between all four raters on the objective components of the SCI-FAI (temporal-distance & assistive device scores).
In the gait parameters component, inter-rater reliability was moderate-good (ICC= 0.703-0.84) and intra-rater reliability was good (ICC= 0.85-0.956). The authors also demonstrated the construct validity of the SCI-FAI as the gait parameter score was shown to significantly correlate with walking speed (r= 0.7-0.742) and the WMS (r= 0.697). In addition, the sensitivity of the SCI-FAI was examined in 19 subjects involved in a walking intervention study. A statistically significant change in mean gait score (44.7%) was found after training and this percentage change moderately correlated with change in LEMS (r= .58).

A few global functional measures have also been used in the SCI literature as measures of walking performance. Of these measures, only the Spinal Cord Independence Measure (SCIM) has specifically designed for this population. Developed by Catz and colleagues (1997), the SCIM was developed as a measure of disability, which specifically addressed aspects of daily living affected by SCI. It consists of 18 items scored on ordinal scales for a total score out of 100. Unlike the FIM, the scaling for each item of the SCIM varies depending on relative level of importance of each task to individuals with SCI. For example, locomotion, bowel, and bladder items were scored out of 8, 10, and 15 respectively whereas different transfer tasks were only scored out of 2. The SCIM includes three items which address walking function: mobility indoors, mobility for moderate distance (10-100 m), and mobility outdoors (> 100 m). In each of these items, wheelchair, walking aids, and orthoses use are included in the ordinal ratings. The SCIM does not however include the degree of physical assistance or supervision in the scale. As a result, an individual who requires some assistance with walking would be scored as dependent on a wheelchair and therefore no walking capability would be captured within this measure. Furthermore, the outdoor mobility item does not include any obstacles such as curbs or uneven terrain.
At present, the SCIM Locomotor items have not been used as a measure of walking ability in any clinical trials although the scale has been used as global measure of function in the SCILT (Dobkin, 2003), EM-SCI (van Hedel, 2008), and the current FES-Walking study that this thesis is a component of. The psychometric properties of the SCIM have been established both in a single centre (Catz et al, 1997, Catz et al., 2001) as well as more recently in an international, multi-centre study (SCIM-III) (Catz, 2007). In fact, the ICCP panel recently concluded that although the SCIM is continuing to undergo scale refinement, it appears to be a more sensitive, accurate, and relevant overall measure of functional ability in SCI (Steeves, 2007).

The Functional Independence Measure (FIM) is perhaps the most commonly used measure of disability in SCI particularly in Canada and the US where it is mandatory in all rehabilitation facilities. The FIM was originally designed to measure burden of care or level of disability in performing basic daily activities (Keith et al., 1987). The FIM consists of 18-items each having a 7-level ordinal scale. It demonstrates strong psychometric properties (Finch et al., 2002) including good reliability (Hamilton, 1994) and construct validity (Dodds, 1993). Though an inverse relationship has been found between neurological level and FIM motor items in SCI, the authors found less sensitivity for locomotor items (Middleton, 1998). In contrast to the SCIM, walking is assessed in only one FIM item. In the assessment of locomotion, the FIM does however differentiate between supervision and varying levels of physical assistance but does not take in to account the types of assistive device used. For the scoring of the overall FIM as used in rehabilitation centres, the degree of physical assistance in locomotion is determined based on an individual’s primary means of mobility. As a result, if an individual is only able to walk for short distances in therapy but uses a wheelchair for the rest of the day then the Locomotor score is based on the degree of independence in the wheelchair only. Although the overall FIM score has been widely used as an indicator of functional improvement, the specific application of the
FIM locomotor item (FIM-L) as a measure of walking performance has been limited. Behrman and Harkema (2000) did however use the FIM-L as a measure of walking disability in a series of case studies examining the effects of a locomotor training intervention. In addition, the FIM-L was been included as the primary outcome measure in subjects with classified as AIS B or C in the SCILT (Dobkin, 2003). In both of these studies, the FIM-L was scored based on the subjects’ walking ability even if they were not necessarily walking as their primary means of mobility.

Although it has been validated and used in clinical trials, the specificity of the FIM-L has been questioned. In an examination of the SCILT data, Ditunno (2007) found that multiple WISCI-II levels for a single FIM-L level. For example, an FIM-L score of 6 represented a range of WISCI-II levels from 8 – 19. These findings illustrate that the FIM-L in isolation does not provide the same degree of specificity as the WISCI-II with respect to assistive device usage since it does not distinguish between different types of assistive devices. Nonetheless, the FIM-L has shown significant correlations at 3, 6 and 12 months with the other SCI walking measures used in the SCILT: WISCI-II ($\rho = .89-.92$); 15.2m walk test ($\rho > .80$); 6MWT ($\rho = .62-.78$) (Ditunno, 2007).
CHAPTER 3: Manuscript # 1 (to be submitted to Spinal Cord)

Relationship between Clinical Measures of Sensorimotor Function and Walking in Chronic, Incomplete Spinal Cord Injury

Study Design: Case series with cross-sectional data.

Objectives: To describe the extent of sensorimotor function and walking ability in a sample of individuals with chronic, incomplete SCI and the relationship between lower extremity sensorimotor function and current clinical walking measures in SCI.

Setting: A SCI rehabilitation centre in Toronto, Canada

Methods: Twenty-five subjects with chronic incomplete SCI were assessed using: ASIA Impairment Scale (AIS), Lower Extremity Motor Score (LEMS), Lower Extremity Pinprick Score (LEPS), and Motor Asymmetry (MA). Walking ability was assessed using 6 standardized measures: FIM-Locomotor Score, Assistive Device (AD) Score, Walking Index for SCI-Version II, 10-metre Walk Test, Timed Up and Go (TUG), Six-Minute Walk Test and Walking Mobility Scale. Pearson’s correlations were used to examine the relationships between variables.

Results: Walking ability and sensorimotor function varied greatly between subjects. LEPS and MA did not significantly correlate to walking ability. LEMS significantly correlated with the majority of walking measures with the exception of the Lower Extremity AD and the TUG. Twenty-one out of 22 ambulatory subjects had a LEMS threshold >20. Non-ambulatory subjects (n=3) did not achieve threshold. The strength of several individual lower extremity muscles also significantly correlated with walking measures.

Conclusion: Walking ability in incomplete SCI is related to lower extremity motor but not to sensory function. It is important in future studies to examine motor function as well as other physical factors in a broad range of subjects across different walking constructs in order to fully understand the determinants of walking in SCI.

Key Words: spinal cord injury, locomotion, gait, muscle strength, sensation, measurement

Introduction

Over half of spinal cord injuries (SCI) are now incomplete in nature. (Go, 1995, Wyndaele, 2006) As a result; the recovery of walking is becoming a realistic possibility for a growing number of individuals. It has been reported that 46–85% of patients will recover some capacity to walk following an incomplete SCI (Burns, 1997, Waters, 1994a,b) however the extent of walking ability is highly variable.

Several walking measures have been newly developed or validated for use in SCI enabling a more comprehensive approach to measurement of walking across different constructs.
such as speed, distance, and level of assistance (van Hedel, 2005). Given the heterogeneity of walking ability in SCI, it is important to understand how clinical factors such as sensation and motor function relate to the different aspects of walking in order to individualize clinical interventions and inform the design of future interventions and research trials.

An important step in this line of inquiry is to understand how current clinical measures of sensorimotor function relate to different components of walking in SCI. The International Standards for Neurological Classification of SCI (ISCI) is the most commonly used measure of sensorimotor function in SCI (Marino, 2003). In a recent review, Scivoletto (2008a) emphasized that the ASIA Impairment Scale (AIS), Lower Extremity Motor Score (LEMS), and having at least anti-gravity strength in the hip flexors and/or quadriceps early post-injury, were key predictors of walking following a SCI (Burns, 1997, Waters, 1994a,b). Lower extremity motor function, both composite motor scores and the strength of individual lower extremity muscle groups, is not only an important predictor but also a major determinant of walking at a given point in time. Studies have found significant relationships between LEMS and walking status (Kim, 2004, Scivoletto, 2008b, Curt, 1998). In individuals with chronic incomplete SCI, Kim (2004) found significant relationships between walking and the strength of individual muscle groups. In particular, the proximal muscles of the less affected side were a major determinant of walking speed, distance, and ambulatory capacity. Scivoletto (2008b) also demonstrated significant relationships between walking and the following measures: LEMS; proximal LEMS; Berg Balance Scale; and Modified Ashworth Scale. Although several studies have examined the influence of motor function on walking, in contrast, the role of sensory function on walking in SCI has only been minimally examined (Scivoletto, 2008a).

The classification of motor-incomplete SCI represents a diverse range of sensorimotor and therefore, functional abilities. Similarly, walking is a complex function that can be
measured across several domains. Given that validated walking measures now exist for SCI, it is possible to examine in more detail, how standard clinical measures such as the components of the ISCSCI examination relate to the different components of walking in a broad range of individuals with incomplete SCI. The objectives of this study are to describe the extent of sensorimotor function and walking ability in individuals with chronic, incomplete SCI and the relationship between lower extremity sensorimotor function and different components of walking.

Methods

Subjects

This research focuses on a spectrum of current SCI walking measures to determine if sensorimotor function is related equally to different components of walking. Twenty-five individuals with chronic, incomplete SCI were studied. This cross-sectional study involved a sample of convenience of subjects enrolled in a clinical trial focused on the use of FES-assisted walking for the reduction of secondary complications following SCI. To be eligible for inclusion, subjects must have sustained a traumatic SCI; motor-incomplete (AIS C or D); and be at least 18 months post-injury. In addition, participants could not have any contraindications for FES, such as cardiac pacemakers, skin lesions at potential electrode sites, or denervation of targeted muscles. Participants were also excluded if they had pressure ulcers anywhere on the lower extremities, or if they suffer from any of the following cardiovascular conditions: (1) hypertension that is uncontrolled; (2) symptoms of orthostatic hypotension when standing for 15 minutes; or (3) susceptibility to autonomic dysreflexia, requiring medication. The study was approved by the university and hospital ethics boards and all subjects were informed of study details prior to giving consent to participate.
**Procedures**

Neurological levels and AIS were determined in accordance with the International Standards for Neurological Classification of SCI guidelines (Appendix 2) (Marino, 2003). The LEMS and Lower Extremity Pinprick Score (LEPS) were derived from the ISCSCI examination. The LEPS was comprised of bilateral pinprick sensation testing for the L2-S2 dermatomes using a 3-point scale (0-2) for a total score out of 24. The LEMS was comprised of bilateral lower extremity manual muscle testing of 5 key muscle groups (hip flexors, knee extensors, ankle dorsiflexors, great toe extensors, and plantar flexors) using a standardized 6-point scale. Proximal and distal LEMS were calculated based on sub-scores for the two most proximal and three most distal muscle groups respectively. A Motor Asymmetry (MA) score was calculated based on the relative difference between the right and left lower extremity motor scores.

A physical therapist performed a battery of walking measures (Appendix 3) in order to determine the extent of walking ability across different constructs. The measures were as follows: Functional Independence Measure – Locomotor Score (FIM-L) (Hall, 1999), Total Assistive Device Score (Total AD) comprised of the Upper Extremity (UE AD) and Lower Extremity Assistive Device (LE AD) Scores (Field-Fote, 2001), Walking Index for Spinal Cord Injury – Version Two (WISCI-II) (Ditunno, 2001), Ten-meter Walk Test (10mWT), Timed Up & Go (TUG), Six-minute Walk Test (6MWT) (van Hedel, 2005) and Walking Mobility Scale (WMS) (Field-Fote, 2001). Prior to using these measures to assess walking ability, each subject’s ability to stand and initiate steps was determined. If unable to walk 10 meters with less than or equal to moderate assistance, scores were only recorded for the FIM-L, WISCI-II, and WMS.

Short distance walking velocity was calculated by recording the time required to walk 10 meters. For the 10mWT (van Hedel, 2005), subjects were asked to walk as fast as they safely
could for a total of 14 meters to account for acceleration and deceleration. Three other measures were also obtained during the 10mWT. The FIM-L measured the amount of physical assistance and independence in walking based on a seven-point ordinal scale (Hall, 1999). The Total AD score was adopted from the SCI-Functional Ambulation Inventory (Field-Fote, 2001). The UE AD and LE AD scores rated the degree of assistive device usage deemed necessary for safety and comfort for a total AD score out of 14. The WISCI-II combined assistive devices and physical assistance into a 21-level hierarchal scale (Ditunno, 2001). Although there is a high degree of overlap between the FIM-L, AD scores, and WISCI-II, all three measures were used to examine the relative contributions of the 3 constructs of physical assistance, LE AD, and UE AD and how they related to sensorimotor function. The TUG measured the timed performance of rising from a chair, walking 3 meters, turning, and walking back to the chair to sit down (Podsiadlo, 1999). To complete the TUG, subjects had to be able to independently sit-to-stand.

In the 6MWT, subjects were asked to walk as far as possible for 6 minutes along a flat hallway with the total distance walked recorded (van Hedel, 2005). The WMS, also adopted from the SCI-Functional Ambulation Inventory (Field-Fote, 2001) consists of a 5-point scale based on categories described by Perry (1995). The WMS reflects the extent of household and community ambulation, providing an overall rating of walking participation.

Data analysis

Descriptive statistics were performed on all study variables. Pearson’s product-moment correlations were used to quantify relationships between variables. The relationship between LEMS and 10mWT was further analyzed using both linear and non-linear regression to determine best fit curve. For all analyses, significance was set at an alpha level of 0.05.

Statistical analysis was performed using SPSS software (version 13.0).
Statement of Ethics

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Results

Subject demographic and neurological characteristics are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Sample demographics and neurological status (n = 25)</th>
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</thead>
<tbody>
<tr>
<td>Variable</td>
<td>n</td>
</tr>
<tr>
<td>Age ( years )</td>
<td></td>
</tr>
<tr>
<td>Gender ( M / F )</td>
<td>20/5</td>
</tr>
<tr>
<td>Time Post-Injury ( years )</td>
<td></td>
</tr>
<tr>
<td>Tetraplegia</td>
<td>19</td>
</tr>
<tr>
<td>Paraplegia</td>
<td>6</td>
</tr>
<tr>
<td>ASIA Impairment Scale (C/ D)</td>
<td>11/14</td>
</tr>
<tr>
<td>LEPS (/24)</td>
<td>24</td>
</tr>
<tr>
<td>LEMS (/50)</td>
<td>25</td>
</tr>
<tr>
<td>Motor Asymmetry</td>
<td>25</td>
</tr>
<tr>
<td>More affected limb ( R / L / E )</td>
<td>14/10/1</td>
</tr>
</tbody>
</table>

M: male; F: female; R: right; L: left; E: equal

Sensory function as measured by LEPS was impaired in all 25 subjects ranging from 0 -16 out of 24. The majority of subjects demonstrated some degree of lower extremity motor asymmetry however the extent of asymmetry varied greatly. Table 2 summarizes the strength of individual lower extremity muscle groups. In this cohort, the distal muscle groups, (plantar flexors, dorsiflexors, and great toe extensors) of the more affected side, were weakest. In particular, in their more affected limb, none of the subjects had greater than anti-gravity strength for the plantar flexors and only two subjects for ankle dorsiflexors. Also, two subjects showed no active movement in their ankle dorsiflexors and six subjects had no active movement in the great toe extensors on their more affected side.
Table 2  Strength of individual lower extremity muscle groups (n = 25)

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>Side</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Flexors (L2)</td>
<td>More affected</td>
<td>2.8</td>
<td>1.5</td>
<td>3</td>
<td>0 - 5</td>
</tr>
<tr>
<td></td>
<td>Less affected</td>
<td>3.9</td>
<td>1.1</td>
<td>4</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Knee Extensors (L3)</td>
<td>More affected</td>
<td>2.8</td>
<td>1.3</td>
<td>3</td>
<td>0 - 5</td>
</tr>
<tr>
<td></td>
<td>Less affected</td>
<td>4.0</td>
<td>1.2</td>
<td>4</td>
<td>0 - 5</td>
</tr>
<tr>
<td>Ankle Dorsiflexors (L4)</td>
<td>More affected</td>
<td>1.9</td>
<td>1.1</td>
<td>2</td>
<td>0 - 4</td>
</tr>
<tr>
<td></td>
<td>Less affected</td>
<td>3.4</td>
<td>1.2</td>
<td>4</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Great Toe Extensors (L5)</td>
<td>More affected</td>
<td>1.9</td>
<td>1.5</td>
<td>2</td>
<td>0 - 4</td>
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<tr>
<td></td>
<td>Less affected</td>
<td>3.3</td>
<td>1.3</td>
<td>4</td>
<td>0 - 5</td>
</tr>
<tr>
<td>Ankle Plantarflexors (S1)</td>
<td>More affected</td>
<td>1.6</td>
<td>0.6</td>
<td>2</td>
<td>0 - 3</td>
</tr>
<tr>
<td></td>
<td>Less affected</td>
<td>2.6</td>
<td>1.1</td>
<td>2</td>
<td>1 - 5</td>
</tr>
</tbody>
</table>

Table 3 describes the overall walking characteristics within the sample. Walking ability varied greatly amongst subjects and between walking measures.

Table 3  Descriptive summary of clinical walking measures

<table>
<thead>
<tr>
<th>Walking Measure</th>
<th># able to complete measure</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Range</th>
</tr>
</thead>
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<tr>
<td>FIM – L (1 – 7)</td>
<td>25</td>
<td>4.4</td>
<td>1.8</td>
<td>5</td>
<td>1 - 7</td>
</tr>
<tr>
<td>UE AD (0 – 8)</td>
<td>22</td>
<td>2.5</td>
<td>2.1</td>
<td>2</td>
<td>0 - 8</td>
</tr>
<tr>
<td>LE AD (0 - 6)</td>
<td>22</td>
<td>5.5</td>
<td>1.3</td>
<td>6</td>
<td>1 - 6</td>
</tr>
<tr>
<td>TOTAL AD (0 – 14)</td>
<td>22</td>
<td>8</td>
<td>2.2</td>
<td>8</td>
<td>5 - 14</td>
</tr>
<tr>
<td>WISCI– II (0 – 20)</td>
<td>25</td>
<td>9.2</td>
<td>6.2</td>
<td>13</td>
<td>0 - 20</td>
</tr>
<tr>
<td>10mWT (m/s)</td>
<td>19</td>
<td>0.43</td>
<td>0.43</td>
<td>0.35</td>
<td>0.05 - 1.67</td>
</tr>
<tr>
<td>TUG (s)</td>
<td>14</td>
<td>55.1</td>
<td>10.5</td>
<td>53.1</td>
<td>9.8 - 122.6</td>
</tr>
<tr>
<td>6MWT distance (m)</td>
<td>13</td>
<td>152.7</td>
<td>123.3</td>
<td>114.0</td>
<td>28.7 - 413.9</td>
</tr>
<tr>
<td>WMS (1 - 5)</td>
<td>25</td>
<td>2.2</td>
<td>1.3</td>
<td>2</td>
<td>1 - 5</td>
</tr>
</tbody>
</table>

The relationships between LEPS, LEMS, MA, strength of individual lower extremity muscle groups and walking measures is presented in Table 4. No significant correlations were found between LEPS and any walking measures. As expected, LEMS significantly correlated with the majority of walking measures apart from the TUG which approached significance and the LE AD. Both the FIM-L and WISCI-II were highly correlated with LEMS.
### Table 4a Relationship between sensorimotor function & walking measures

<table>
<thead>
<tr>
<th></th>
<th>FIM</th>
<th>UE AD</th>
<th>LE AD</th>
<th>Total AD</th>
<th>WISCI</th>
<th>10mWT</th>
<th>TUG</th>
<th>6MWT</th>
<th>WMS</th>
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<tr>
<td><strong>SENSORY</strong></td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>LEPS</td>
<td>.140</td>
<td>.393</td>
<td>-.317</td>
<td>.173</td>
<td>.316</td>
<td>.120</td>
<td>.205</td>
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<td><strong>MOTOR</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEMS</td>
<td>.759**</td>
<td>.503*</td>
<td>.138</td>
<td>.555*</td>
<td>.700**</td>
<td>.598**</td>
<td>-.525</td>
<td>.622*</td>
<td>.562**</td>
</tr>
<tr>
<td>PLEMS</td>
<td>.664**</td>
<td>.610**</td>
<td>.053</td>
<td>.605**</td>
<td>.659**</td>
<td>.509*</td>
<td>-.184</td>
<td>.468</td>
<td>.549**</td>
</tr>
<tr>
<td>DLEMS</td>
<td>.707**</td>
<td>.295</td>
<td>.175</td>
<td>.381</td>
<td>.613**</td>
<td>.569*</td>
<td>-.619*</td>
<td>.561*</td>
<td>.475*</td>
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<tr>
<td>MA</td>
<td>.090</td>
<td>-.046</td>
<td>-.514*</td>
<td>-.346*</td>
<td>-.003</td>
<td>.001</td>
<td>-.003</td>
<td>-.023</td>
<td>.191</td>
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<tr>
<td>LAf Hip Flex</td>
<td>.580**</td>
<td>.436*</td>
<td>-.354</td>
<td>.023</td>
<td>.421*</td>
<td>.373</td>
<td>.016</td>
<td>.345</td>
<td>.500*</td>
</tr>
<tr>
<td>MAf Hip Flex</td>
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<td>.344</td>
<td>.445*</td>
<td>.689**</td>
<td>.484*</td>
<td>.471*</td>
<td>-.434</td>
<td>.503</td>
<td>.390</td>
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<tr>
<td>LAf Knee Ext</td>
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<td>.623**</td>
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<td>.492*</td>
<td>.502*</td>
<td>.363</td>
<td>-.139</td>
<td>.225</td>
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<tr>
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<td>.500*</td>
<td>.112</td>
<td>.599**</td>
<td>.603**</td>
<td>.518**</td>
<td>-.044</td>
<td>.419</td>
<td>.469*</td>
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<td>LAf Dorsiflex</td>
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<td>-.239</td>
<td>.026</td>
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<td>.531**</td>
<td>-.294</td>
<td>.555*</td>
<td>.501*</td>
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<td>.224</td>
<td>-.194</td>
<td>.313</td>
<td>.423*</td>
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<td>-.301</td>
<td>.069</td>
<td>.487*</td>
<td>.412*</td>
<td>-.503</td>
<td>.528</td>
<td>.500*</td>
</tr>
<tr>
<td>MAf Toe Ext</td>
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<td>.039</td>
<td>.323</td>
<td>.415</td>
<td>.434*</td>
<td>.432*</td>
<td>-.586*</td>
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<td>.277</td>
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<td>LAf Pl. Flex</td>
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<td>-.018</td>
<td>.157</td>
<td>.530**</td>
<td>.433*</td>
<td>-.315</td>
<td>.257</td>
<td>.667**</td>
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<td>.040</td>
<td>.200</td>
<td>.440*</td>
<td>.339</td>
<td>-.264</td>
<td>.346</td>
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</tbody>
</table>

PLEMS: Proximal LEMS; DLEMS: Distal LEMS; MA: Motor Asymmetry; MAf: Most Affected; LAf: Least Affected; * Significant at $P < 0.05$, ** significant at $P < 0.01$

### Table 4b Significance of the relationships between motor function and walking measures

<table>
<thead>
<tr>
<th></th>
<th>FIM</th>
<th>UE AD</th>
<th>LE AD</th>
<th>Total AD</th>
<th>WISCI</th>
<th>10mWT</th>
<th>TUG</th>
<th>6MWT</th>
<th>WMS</th>
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<tbody>
<tr>
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<td>.000**</td>
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<td>.539</td>
<td>.007*</td>
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<td>.016*</td>
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<td>.038*</td>
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<tr>
<td>LAf Pl. Flex</td>
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<td>.260</td>
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<td>.098</td>
<td>.361</td>
<td>.247</td>
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</table>

PLEMS: Proximal LEMS; DLEMS: Distal LEMS; MA: Most Affected; LAf: Least Affected; * Significant at $P < 0.05$, ** significant at $P < 0.01$
Figure 2 shows the relationship between LEMS and 10mWT demonstrating that a non-linear model best describes this relationship (p=0.001). It is noteworthy that with the exception of one outlier (LEMS=18), all of the subjects who were able to stand and initiate steps had a LEMS≥20. However, none of the subjects who couldn’t stand achieved this LEMS threshold. It also appears that walking speed increases at a greater rate at approximately LEMS≥30.

**Figure 2: Relationship between Lower Extremity Motor Scores (LEMS) and Walking Speed during 10mWT.** A non-linear regression model was used display best fit curve. The dashed vertical line delineates LEMS=20. Waters\textsuperscript{20} found that subjects with LEMS<20 were limited ambulators who were less efficient and relied heavily on upper extremities and those with LEMS>30 were community ambulators.

MA did not correlate significantly with most walking measures. The LE AD scores were not correlated significantly with most measures of sensorimotor function with the exception of the
more affected hip flexors ($r=0.445$) and MA ($r=-0.514$) which seems reasonable since the three subjects who used lower extremity orthoses used them unilaterally. Both proximal and distal LEMS showed moderately significant correlations ($r= 0.5-0.7$) with several walking measures. Finally, the strength of several individual muscle groups correlated significantly with walking measures. In fact, the strength of three muscle groups: the less affected knee extensors, more affected hip flexors, and less affected plantar flexors, actually had the higher correlations with the UE AD score, total AD score and WMS respectively than did the total LEMS.

Discussion

Our study sought to better understand the relationship between clinical measures of sensorimotor function and walking in individuals with chronic, motor-incomplete SCI participating in a research trial. The cohort was heterogeneous in terms of duration post-injury, sensorimotor function and walking ability. In contrast to similar studies (Kim, 2004, Scivoletto, 2008b, van Hedel, 2006), our study was not limited to individuals who were already functional walkers which allowed examination through a broader range of subjects with potential walking ability. In one of the studies, subjects with motor-complete SCI as well as lower motor neuron injuries were also included whereas our criteria specified motor-incomplete excluding lumbar or sacral SCI (Scivoletto, 2008b).

The relationship of sensory function as measured through the International Standards and walking has only been minimally investigated (Marino, 2003). Examining the significance of motor-evoked potentials and ASIA scores to functional outcomes, Curt (1998) found significant correlations ($r_s=0.53 - 0.74$) between ambulatory capacity and ASIA sensory scores in both acute and chronic SCI. However, direct comparison to our study is difficult since AIS classifications were not specified. Other studies focused specifically on individuals initially diagnosed as
sensory-incomplete (AIS B) (Crozier, 1991, Oleson, 2005). In a retrospective study, Crozier (1991) found the presence of pinprick in addition to light touch sensation below the level of injury was associated with significantly better prognosis for functional walking than having only light touch preservation. In the largest study to date, Oleson (2005) showed that early pinprick sensation, both sacral and lower extremity, were associated with improved walking prognosis. It is believed that the close anatomical proximity of the spinothalamic tract to motor tracts is the basis for the prognostic benefit of pinprick sensation (Crozier, 1991, Oleson, 2005). Beyond the studies discussed, little evidence exists regarding the contribution of sensation to walking in SCI. Our results provide no further supportive evidence regarding a sensory relationship with walking. This paucity of evidence does not disregard the purported importance of sensation for walking but highlights the need for more sensitive, quantitative, and comprehensive sensory measures that also include other modalities such as vibration and proprioception before drawing definite conclusions (Hayes, 2002).

In contrast, there is strong evidence that lower extremity motor function is a major determinant of walking ability. Several authors have demonstrated significant relationships between LEMS and walking status (Kim, 2004, Scivoletto, 2008b, Waters, 1994c). Our results show similar significant relationship to all comparable walking measures however Kim (2004) demonstrated stronger correlations than the present study. This may be explained by the differences in the sample characteristics such as our inclusion of individuals with little or no walking ability, the predominance of individuals with asymmetrical motor weakness in the Kim study or the potential that other factors such as balance could have also influenced our cohort. We also found that LEMS did not significantly correlate with TUG. Although the small sample size (14 subjects were assessed using the TUG) may account for this finding, it suggests that
performance on components of the TUG may rely strongly on factors not examined such as trunk muscle strength.

With the exception of one outlier, subjects with LEMS<20 were unable to walk. In examining data from three studies which required functional walking as inclusion criteria (Kim, 2004, Scivoletto, 2008b, van Hedel, 2006), we found that none of the subjects in these studies had LEMS lower than our suggested threshold of 20. Interestingly, our findings also relate to previous work by Waters (1994c) in which individuals with LEMS<20 were limited ambulators who were less efficient and relied heavily on their upper extremities whereas those with LEMS>30 were community ambulators. With this growing evidence, it may be possible to set a LEMS≥20 as a threshold level for being able to walk and LEMS≥30 for community walking in incomplete SCI. As such, the exploration of these proposed threshold levels of lower extremity motor function for walking warrants further study.

Although lower extremity strength is a critical determinant for walking, the examination of our subject outliers suggests the potential importance of other biological and personal factors being critical in individual cases. For example, subject # 9 performed well on all walking measures despite having a LEMS=18 which may be attributable to other factors such as age (22 years) and a significant motivation to walk. In contrast, subject # 17 had a LEMS score of 37 yet was unable to independently sit-to-stand and required assistance to walk 10 meters at velocity of only 0.08 m/s. A high body mass index (34.4 kg/m^2) and observed reduced balance may explain these results.

Early work by Hussey (1973) demonstrated that proximal lower extremity strength (pelvic control, hip flexors, and quadriceps) is an important requirement for ambulation. More recently, significant correlations have been found between proximal LEMS and walking measures (Scivoletto, 2008b). Furthermore, Kim (2004) showed that proximal muscle strength,
particularly of the less affected side, was an important determinant of walking ability. Specifically, the strength of the less affected hip flexors accounted for 50% of the variance in 10mWT and 6MWT whereas the strength of the less affected hip extensors accounted for 64% of ambulatory capacity. Although our study also found significant correlations between proximal LEMS and most walking measures, in contrast to Scivoletto (2008b), proximal LEMS did not correlate as strongly as total LEMS and for four measures, relationships were actually stronger with distal than proximal LEMS.

The strength of individual lower extremity muscles has also been identified as a determinant of walking ability in SCI. It has been suggested that to be an effective community ambulator, an individual must have at least anti-gravity strength in the knee extensors on one side (Hussey, 1973, Crozier, 1992). Although 22 out of 25 subjects in our study demonstrated at least grade 3 strength in their knee extensors on one side, this clearly did not equate to community walking. Our study confirmed Kim and colleagues (2004) findings that individual lower extremity muscle groups relate to walking measures albeit differences were found in which muscle groups were most significant. Clearly there may be the potential for the strength of individual muscles to contribute substantially to walking but cannot be considered an exclusive determinant of walking in SCI.

Both our study and Kim et al. (2004) found that the knee extensors were the strongest muscle group and the ankle dorsiflexors were among the weakest. We also found that additional distal muscle groups were more affected, posing questions about underlying mechanisms such as the influence of neuroanatomy, secondary neuropathology, patterns of motor recovery or previous rehabilitation.

In summary, by studying a broader range of individuals with incomplete SCI across multiple walking constructs, the present study provides further insight into the relationship
between lower extremity strength and walking ability in SCI. Specifically, future studies are required to confirm: 1) the proposed LEMS threshold; 2) the relationship of individual muscle groups to walking; and 3) the distribution of strength across different muscle groups.

Understanding these components could have significant implications in terms of prognosis early post-injury and to inform interventions. Our results confirm that while lower extremity motor strength is important, it is not the sole factor related to walking in SCI and support the future investigation of both sensation and postural control ensuring that specific measures are used to elucidate these potential relationships.
Relationships between validated walking measures in chronic, incomplete SCI: Clinical and research implications

Background: Walking is a realistic possibility for many individuals with incomplete SCI however the extent of walking ability varies greatly. Several walking measures have been validated for use in SCI however it remains unclear which measures should be used for clinical practice and different types of research trials.

Objectives: 1) To examine how current SCI walking measures describe walking ability in a cross-section of individuals with chronic motor-incomplete SCI; 2) To understand the interrelationships between SCI walking measures; and 3) To determine whether the 6MWT can provide meaningful information beyond the 10mWT in chronic incomplete SCI.

Method: The study involved 25 subjects with chronic, traumatic motor-incomplete SCI participating in a clinical trial. Subjects were assessed using a battery of walking measures consisting of the FIM-Locomotor Score, Assistive Device Score, Walking Index for SCI-Version II, 10-metre Walk Test (10mWT), Timed Up and Go (TUG), Six-Minute Walk Test (6MWT) and Walking Mobility Scale. Prior to initiating the battery of walking measures, each subject’s ability to stand and initiate steps was assessed.

Results: Not all subjects were able to complete all of the walking measures. Nineteen subjects completed the 10mWT however five subjects were unable to complete the TUG and six were unable to complete the entire 6MWT. Walking ability varied amongst subjects and between walking measures. Most walking measures were significantly related, with exception of correlations involving LE AD. While the 10mWT and 6MWT were highly correlated (r= 0.984), those subjects who walked at >0.95 m/s did not reach their predicted 6-minute walk distance.

Conclusions: The use of a battery of walking measures enables a broader description of walking ability across different constructs in individuals with incomplete SCI. In choosing walking measures for both clinical practice and research in SCI, it is important to consider the characteristics of the measure as well as the intent of the intervention.

Key Words: Spinal cord injury, locomotion, gait, mobility, measurement

Introduction

The restoration of walking ability has been ranked one of the highest priorities for recovery by individuals with a spinal cord injury (SCI) (Patrick, 2003). The development of new interventions for the recovery of walking has also become a significant area of focus in SCI research. For example, the largest multicenter randomized clinical trial of locomotor training in
incomplete SCI to date was recently completed (Dobkin, 2006). The results from this trial did not reveal significantly different functional walking outcomes between the treatment and control groups yet produced unprecedented improvements in walking ability in subjects with motor-incomplete SCI using a comprehensive set of validated outcome measures. In light of the above, it is increasingly important to provide objective data regarding walking ability. While a growing number of individuals with incomplete SCI recover the ability to walk (Burns, 1997), some walk slower and less efficiently (Lapointe, 2001), have less capacity to increase speed (Pepin, 2003) and therefore may not use this form of locomotion in the community. As a result, it is important for both clinicians and researchers to detail the extent of walking ability in order to more accurately understand this diverse population.

The measurement of outcomes is an essential aspect of rehabilitation. Rehabilitation measures are considered to have three general purposes; to evaluate change, to predict outcomes, and to discriminate between groups (Cole, 1994). Significant advances have recently been made in outcome measures for walking in SCI and several walking measures have now been validated or developed specifically for SCI. A systematic review of these measures has been completed (Lam, 2008) and the International Campaign for the Cure of SCI Paralysis (ICCP) has made recommendations of measures for clinical trials (Steeves, 2007).

SCI walking measures can be categorized into timed and categorical measures (Lam, 2008). Of the timed measures, the Ten-meter Walk Test (10mWT) (van Hedel, 2005), a measure of walking speed, has been the most widely used in SCI and has been recommended by the ICCP for use in clinical trials (Steeves, 2007). The Timed Up and Go test (TUG), originally developed as a measure of functional mobility in the elderly, has also been validated as a functional walking measure in SCI (Podsiadlo, 1991). The Six-minute Walk Test (6MWT) which measures the distance walked over 6 minutes was validated in SCI (van Hedel, 2005). Although recent studies
suggest that the 6MWT may be redundant in addition to the 10mWT (van Hedel, 2007, Barbeau, 2007, Kim, 2004), some of these studies have identified a subset of subjects who completed the 10mWT but were unable to complete the 6MWT (van Hedel, 2007, Dobkin, 2007). The Walking Index for SCI-Version Two (WISCI-II) (Ditunno, 2001), the SCI-Functional Ambulation Inventory (SCI-FAI) (Field-Fote, 2001), and the Functional Independence Measures (FIM) (Hall, 1999), are categorical walking measures that have been validated in SCI however the use of ordinal scales, where intervals between categories may not be equal, has been criticized. Nonetheless, categorical walking measures have the advantage of capturing both walkers and non-walkers and the transition between these states. Unlike timed measures, they also do not have a minimal distance or time required to complete the test.

In choosing which walking measures to use, it is critical to acknowledge the complexity of walking and the heterogeneity of SCI. Consideration must be given to whether measures will be for clinical decision making or outcomes in clinical trials, the nature and objectives of the intervention and the characteristics of the individuals being measured. It has recently been acknowledged that no one walking measure is ideal but that a combination of walking measures should be used to assess change across different levels of ability and domains of walking (Steeves, 2007). The objectives of the present study are as follows: 1) To examine how current walking measures describe walking ability in a cross-section of individuals with chronic motor-incomplete SCI; 2) To understand the inter-relationships between SCI walking measures; and 3) To determine whether the 6MWT can provide meaningful information beyond the 10mWT in chronic incomplete SCI.

Methods
Subjects
The study utilizes the baseline data from a clinical trial focusing on FES-assisted walking for the reduction of secondary complications following SCI. This sample of convenience consisted of twenty-five individuals with SCI who completed baseline testing for the clinical trial. The inclusion criteria for the clinical trial were as follows: traumatic SCI; at least 18 months post-injury; motor-incomplete (ASIA Impairment Scale C or D). The study was approved by the university and hospital ethics boards and all subjects were informed of study details prior to giving consent to participate.

Procedures

As part of baseline testing for the clinical trial, each subject’s walking ability was assessed by a physical therapist using a battery of walking measures which included: the FIM–Locomotor Score (FIM-L) (Hall, 1999), Total Assistive Device Score (Total AD) made up of Upper Extremity (UE AD) and Lower Extremity Assistive Device (LE AD) Scores (Field-Fote, 2001), WISCI-Version Two (WISCI-II) (Ditunno, 2001), 10mWT, TUG, 6MWT (van Hedel, 2005) and Walking Mobility Scale (WMS) (Field-Fote, 2001) (Appendix 3). Since inclusion in the clinical trial did not require functional walking ability, each subject’s ability to stand and initiate steps was tested before initiating the formal battery of walking measures. If subjects had not been routinely walking prior to testing, the assessment was initially performed in the parallel bars to ensure safety. To be considered “able to stand and initiate steps”, participants had to be able to stand with no more than moderate assistance and initiate at least 3 steps consecutively. If they were able to complete this task, they were asked to continue walking up to 10 meters. If they could not walk 10 meters with less than or equal to moderate assistance, scores were only recorded for the FIM-L, WISCI-II, and WMS. If subjects were able to walk 10 meters, the complete walking battery was initiated.
The 10mWT was used as a measure of short distance walking speed (van Hedel, 2005). Subjects were asked to walk as fast as they safely could for 14 meters. Standardized instructions were provided and timing began when the lead leg crossed the start line and stopped when their first foot crossed the 10-metre line. A digital stopwatch was used to measure the time to walk the middle 10 meters with two meters at the start and finish to account for acceleration and deceleration. Two trials were performed with the fastest time being recorded for analysis. Walking velocity in meters per second was then calculated. Three other measures, the FIM-L, AD and WISCI-II, were obtained during the 10mWT. The FIM-L measured the amount of physical assistance and independence in walking based on a seven-point ordinal scale (Hall, 1999). For the purpose of our study, the FIM-L quantified the degree of physical assistance to walk even if a wheelchair was the subject’s primary means of mobility. The Total AD score was adopted from the SCI-Functional Ambulation Inventory (Field-Fote, 2001). The UE AD and LE AD scores rated the degree of assistive device usage deemed necessary for safety and comfort out of 8 and 6 respectively for a total AD score out of 14. The WISCI-II is a 21-level functional capacity scale which incorporates both assistive devices and physical assistance (Ditunno, 2001). Although there is a high degree of overlap between the FIM-L, AD scores, and WISCI-II, all three measures were used to examine the relative contributions of the constructs of physical assistance, lower extremity assistive devices, and upper extremity assistive devices and how these measures performed within a broad range of walking ability. The TUG measured the timed performance of rising from a chair, walking 3 meters, turning, and walking back to the chair to sit down (Podsiadlo, 1991). Both the instructions and the test administration were standardized. In order to complete the TUG, subjects had to be able to independently sit-to-stand. Timing started when the subject was no longer in contact with the backrest of the chair and stopped when contact was made with the backrest. In the 6MWT, subjects were asked to walk as far as
possible using their preferred assistive device for 6 minutes along a flat 25-metre hallway to minimize turns with the total distance walked recorded (van Hedel, 2005). Consistent with previous SCI studies, subjects were encouraged to walk as far as possible and not permitted to sit down to rest during the test (Barbeau, 2007, Kim, 2004). The distance walked was recorded at 2, 4 and 6 minutes in the event that subjects were not capable of walking for the entire 6 minutes. The WMS, also adopted from the SCI-Functional Ambulation Inventory (Field-Fote, 2001), consists of a 5-point scale based on categories described by Perry (1995). It reflects the typical walking practice or the extent of household and community ambulation, providing a more global rating of overall walking participation.

Data Analysis
Descriptive statistics were performed on all study variables. To compare the number of subjects able to perform each of the walking tests, frequency analysis was used. Pearson’s product-moment correlations were used to quantify relationships involving at least one interval variable. When both variables were ordinal, Spearman’s rank correlations were used. A paired-samples student’s t-test and linear regression analysis were used to compare walking speeds during the 10mWT and 6MWT. The 10mWT speed was used to determine a predicted 6MWT distance. A repeated-measures ANOVA was used to analyze the distances walked during the three intervals of the 6MWT to determine whether these distances was comparable. For all analyses, significance was set at an alpha level of 0.05. Statistical analysis was performed using SPSS software (version 13.0).

Statement of Ethics
We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Results

Table 5 summarizes the subject demographics. The individual walking characteristics of all subjects are presented in Table 6 in order of walking speed during the 10mWT. Walking ability varied greatly amongst subjects and between walking measures. Of the 25 subjects studied, 3 were unable to stand and initiate steps independently, 3 could stand & initiate at least 3 steps but were unable to walk 10 meters, and the remaining 19 subjects were able to walk at least 10 meters. When examining the 6MWT, n=17 were able to walk for 2 minutes, n=14 walked for 4 minutes, and n=13 were able to complete the entire 6mWT, yet the total distance walked varying greatly. Although the total distance walked for the TUG is less than the 10mWT, five subjects did not complete the TUG because they could not independently sit-stand however, once assisted into standing, could complete the 10mWT. Results from the WMS also highlight another valuable dimension of walking, the extent of home and community walking. Only two subjects were full-time community ambulators (#2 & 4), and three were part-time community ambulators (#1, 3, and 6) whereas six subjects (#17 - 22) were classified as non-functional or exercise-only ambulators.

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</tr>
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Table 6  Individual neurological status and characteristics of walking ability in order of 10mWT speed

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<th>UE</th>
<th>LE</th>
<th>Total</th>
<th>WISC</th>
<th>WMS</th>
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<th>4 min dist</th>
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<td>0-6</td>
<td>0-14</td>
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N: not able to stand or walk; S: stand & initiate ≥ 3 steps; W: walk 10m ≤ moderate assist; n/t: not tested; X: unable to perform test; *: measured during 10mWT

Figure 3 demonstrates the number of subjects who completed each measure as well as the distribution of scores. Not only were all of the subjects not able to complete all of the measures but the distribution of results between measures also varied greatly.
Table 7 presents the correlations between all of the walking measures. The majority of walking measures were significantly correlated at $p < 0.05$. Very high positive relationships (0.90-1.0) were found between: 1) 10mWT and 6MWT; 2) FIM-L and 6MWT; 3) FIM-L and WMS. All of the non-significant correlations included AD scores particularly the LE AD which correlated significantly with only the Total AD.
**Figure 3: Distribution of Walking Measures.** Shown are the box plots of each of the walking measures for all subjects who completed the measure. The box plots depict the median value and interquartile range for each of the measures. 2MWD: Distance walked in metres during 1st 2 minutes of 6MWT; 4MWD: Distance walked (m) during the 1st 4 minutes of 6MWT; 6MWD: Total distance walked in meters over entire 6MWT.

**Table 7 Interrelationship of walking measures**

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<th></th>
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<th>LE AD</th>
<th>Total AD</th>
<th>WISCI</th>
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The bottom left side of table 3 presents the correlations between walking measures. Pearson’s correlations are denoted in standard font & Spearman’s correlations in italics. * indicates significance at $P <0.05$, ** indicates significance at $P <0.01$. The shaded top right side of table 3 presents the actual $p$ value for significance.

Figure 4 demonstrates the strong relationship between the 10mWT and 6MWT however it should be noted that six subjects who completed the 10mWT were unable to complete the 6MWT. For the 13 subjects who completed both tests, a paired-samples t-test demonstrated a significant mean difference of 0.12 m/s ($t=2.7, p=0.019$) in walking speed between the 10mWT.
and the 6MWT. The relationship between the tests was quantified by the following linear regression equation: 6mWT speed = 0.707 x 10mWT speed + 0.043. A predicted distance walked over 6 minutes was also calculated from 10mWT speed (Figure 5). A repeated-measures ANOVA (within-subject condition) was also conducted to determine if significant differences existed between the distances walked during the three 2-minute intervals of the 6MWT for those who could complete the entire 6MWT. Because Mauchly’s test of sphericity was significant ($p < .001$), the Greenhouse-Geisser correction is reported. There was a main effect for distance, $F (1.276, 15.312) = 13.852, \ p < .01, \ \eta_p^2 = .54$. The best fitting model was the linear model, $F (1, 12) = 15.489, \ p < .01, \ \eta_p^2 = .56$. Pairwise comparisons indicated that there was a significant decrease in the distance walked from the 1st – 2nd interval, and 1st – 3rd interval ($p < .01$) but no significant difference between the distance walked during the 2nd and the 3rd 2-minute interval of the 6MWT.
Figure 4. Walking speed during the 10mWT and 6MWT (n=13)

\[ R^2 = 0.968 \]
Discussion

In our study, walking ability varied in terms of both the ability to complete all of the measures and the range of scores for each measure. Based on initial screening, subjects separated into three mobility groups: those unable to stand or walk, individuals who could stand and initiate steps and those who could walk at least 10 meters but could not necessarily complete all walking measures. Although this division into three groups requires replication, it provided a clinically relevant description of the overall spectrum of walk ability including the inability to walk. As a result of our broad inclusion criteria and the use of a battery of walking measures, the

Figure 5. Predicted 6-minute walk distance based on 10mWT speed vs. Actual distance walked during the 6MWT. The asterisks denote the difference between the actual distance walked during the 6MWT and the predicted distance walked over 6 minutes based on the 10mWT for subjects walking >0.95 m/s in 10mWT (* = 98 m; ** = 82 m; *** = 186 m)
present study demonstrates greater heterogeneity in walking ability within chronic incomplete SCI (AIS C & D) than previously reported, where fewer measures were used and only functional walkers were included (Kim, 2004, van Hedel, 2006). For example, inclusion in both the Kim (2004) and van Hedel (2006) studies required that subjects were able to walk at least 6 minutes.

In total, seven walking measures were employed. Although this approach may appear excessive, the time to complete the battery of measures was not a factor since three of the measures (FIM-L, WSCI-II, AD scores) were completed simultaneously during the 10mWT and all of the measures with the exception of the 6MWT required less than 5 minutes to complete. By using a range of walking measures, we demonstrated that walking ability is not consistent across different measures and that important details can be lost by using a single measure. For example, using a single measure may limit one’s ability to determine the spectrum of walking ability in different contexts. In particular, the inclusion of the WMS as a measure of walking participation demonstrated the disparity between being able to walk 10 meters and the extent to which subjects actually utilize walking in their home and environment. Clearly, evaluating one’s walking ability needs to be context dependent. For example, some meaningful environmental challenges may be to cross an intersection or to walk within a grocery store, each with different speed and distance requirements. Only two subjects (#1 & 2) achieved sufficient speed during the 10mWT to cross an intersection safely (1.06 m/s) and sufficient distance during the 6MWT for functional community walking (342 m) although others may have reached this distance given longer time (Lapointe, 2001).

The present study examined the interrelationship between nine different walking measures or sub-scores of measures (UE & LE AD scores) including the relationships between categorical measures not previously studied. Interestingly, all of the non-significant
relationships found involved the sub-scales of the AD score and in particular, the LE AD which only correlated with Total AD score. This finding is likely explained by the fact that 22 subjects in our study did not use any lower extremity assistive devices. Consistent with previous findings (van Hedel, 2005, Kim, 2004, van Hedel, 2006, Ditunno, 2007), significant relationships were found between the remainder of the walking measures. These significant relationships are not surprising, given that they are all measuring some aspect of walking.

Interesting findings were revealed by examining the influence of upper and lower extremity assistive device usage as well as physical assistance in three similar scales, the FIM-L, WISCI-II, and AD scores. As expected, the WISCI-II and FIM-L were strongly correlated as they both incorporate the use of physical assistance and assistive devices. Although the Total AD score was significantly correlated with the WISCI-II and FIM-L, it was in fact the UE AD sub-score that was more correlated with these measures than the Total AD. The UE AD was in fact more highly correlated with the majority of the walking measures. Although similar constructs are included in the FIM-L, AD scores, and WISCI-II, it is important to understand how they differ. The Total AD measure allows for de-coupling of upper and lower extremity assistive devices and uses a hierarchal scale to distinguish between different types of UE and LE AD. It does not however incorporate physical assistance into the score. In contrast, the FIM-L focuses on the degree of physical assistance required including supervision but does not differentiate between types of assistive devices. The WISCI-II, which demonstrates the strongest psychometric properties of the three measures, incorporates all three components of physical assistance, lower extremity and upper extremity assistive device usage into a single 21-level hierarchal scale (Lam, 2008). Interestingly, the WISCI-II differentiates between types of upper extremity assistive devices but does not distinguish between types of lower extremity orthoses or the extent of physical assistance although this information can be included as descriptors.
Although the FIM is widely used, it has been cited that the FIM is not SCI-specific (Lam, 2008) and lacks the specificity of the WISCI (Ditunno, 2007). It is important to consider what components of the FIM are being used e.g. total FIM score, FIM motor score or FIM-L score. Our study utilized the FIM-L as a measure of the extent of physical assistance required during walking. In accordance with Ditunno (2007), our results showed multiple WISCI-II levels for a single FIM-L level. For a FIM-L score of 5, subjects had five different WISCI-II levels ranging from 4 to 13 and for a FIM-L score of 6, five different WISCI-II levels ranging from 9 to 19 were determined. These findings illustrate that the FIM-L in isolation does not provide the same degree of specificity as the WISCI-II with respect to assistive device usage. Consideration must be given to the value of integrating these components into a single scale or whether de-coupling these components into separate measures is more meaningful. Morganti (2005) found that patients at discharge were distributed into 12 out of 21 WISCI-II levels versus 4 out of 7 FIM-L levels. Subjects in the present study were distributed into 10 WISCI-II levels and 6 FIM-L levels. Of the eleven WISCI-II levels not represented in our study, the majority included lower extremity brace usage (8/11) and/or physical assistance (7/11). It has been previously found that certain WISCI-II levels, particularly those which equate to independence in walking, were more frequently used and that regional variations exist in the use of parallel bars and braces between European and US centres (Morganti, 2005, Ditunno, 2008). In our study, WISCI-II levels 8 and 13 which involved the use of a walker with and without physical assistance were the most frequently recorded levels and WISCI-II levels involving braces were minimally used. Our findings further demonstrate that these regional variations in practice warrant consideration in selecting outcomes for multi-center clinical trials. It has also been shown that in individuals with poor walking ability (WISCI-II 0 -10), there were no significant correlations ($r_s=0.20 – 0.24$).
between the WISCI-II and timed measures, which supports the need to include both timed and categorical walking measures in individuals with SCI (van Hedel, 2005).

In contrast to other studies (van Hedel, 2007, Kim, 2004), inclusion in our study was not restricted to individuals who could perform all of the walking tests. If only the 10mWT had been used, overall walking ability would have been over-estimated. Very strong relationships (> 0.95) consistently have been found between the 10mWT (speed) and the 6MWT (distance) in SCI (van Hedel, 2005, 2007, Barbeau, 2007, Kim, 2004). For the subjects in our study who were able to complete both tests, the correlation was also very high (0.984). Barbeau (2007) compared walking speeds during the 15.2 meter and six-minute walk from the SCILT Trial and found that speeds were comparable during these tests except in the highest quartile of walking speeds (0.8-1.0 m/s). Our results showed statistically different walking speeds (mean difference = 0.12 m/s) between the 10mWT and 6MWT. In SCI, 0.06 m/s has been reported as a clinically significant difference in walking speed for the 10mWT (Musselman, 2007). Although we examined differences in walking speed between 2 measures, this previous finding supports the clinical meaningfulness of our results. Similar to Barbeau (2007), walking speeds were similar until a threshold speed of 0.95 m/s was reached at which point subjects walked faster during the 10mWT. Although previous studies have concluded that the 10mWT and 6MWT do not represent separable mobility domains and therefore are not both necessary for clinical trials of locomotion (van Hedel, 2007, Barbeau, 2007, Kim, 2004), this determination warrants further consideration because speed and distance have different functional consequences. For both research and clinical practice, it is important to consider the outcome desired and the objectives of the intervention. Particularly if the intervention is designed to target walking distance, duration, endurance, or community mobility, use of only a short distance walking test (10mWT) lacks specificity. The two walking tests are distinct in terms of instructions and walking duration.
It is highly relevant clinically to monitor progress in terms of the total distance walked and how this distance relates to functional community walking standards (Lapointe, 2001). Understanding and addressing distance requirements is particularly important as part of training in preparation for discharge during inpatient rehabilitation.

In our study, it was anticipated that all subjects may not be able to complete all of the walking measures. Recording the distance walked at 2-minute intervals of the 6MWT provided baseline data when individuals were unable to complete the entire test. It has been suggested that the 6MWT is not always performed in individuals with poor walking ability due to selection bias (van Hedel, 2007). The recording of distances walked at two and four minutes is a minor but important modification to the 6MWT which could minimize selection bias and provide insight regarding fatigability (Dobkin, 2008).

The TUG test has been used as part of the European Multicenter Study of Human SCI (EM-SCI) (van Hedel, 2007). It is simple to administer yet incorporates several relevant walking-related mobility components such as sit-to-stand, gait initiation, and turning. Consistent with findings in the elderly (Podsiadlo, 1991), the completion of the TUG in less than 20 seconds in our study was associated with independent mobility, no assistive device usage and normal walking speeds (subjects # 1 & 2). In addition, had the TUG not been included in our battery of measures, we would not have identified the discrepancy between being able to walk and being able to independently rise from sitting to standing, an essential but often forgotten functional requirement for independence in walking.

The use of the WMS provided valuable information regarding overall walking participation which is the ultimate objective of gait rehabilitation. Kim and colleagues (2004) examined ambulatory capacity as a measure of walking participation using a similar scale (Perry,
1995). Using a multiple regression analysis; they demonstrated that the muscles important for community ambulation differed from those important for walking speed and endurance.

The present study examined the use and relationship of a battery of validated SCI walking measures in individuals with a broad range of walking ability. We demonstrate the value of using multiple walking measures to provide a comprehensive description of overall walking ability. In addition to walking speed, assistive device usage, physical assistance, sit-to-stand capacity, walking distance and walking participation should be considered in order to more accurately reflect the overall complexity of walking. As well, the clinimetrics of the measures, alignment with the population and targeted interventions and the capacity to detect clinical important change are paramount for future studies and clinical practice.

CHAPTER 5: General Discussion

The present study sought to understand the relationships between sensorimotor function and different components of walking in individuals with chronic, incomplete SCI. Grounded in a theoretical framework that integrated the determinants of normal walking and of a model of community mobility, the study examined existing clinical measures, commonly used in SCI research and practice, in order to further understand how they related to each other as well as to the broader concept of overall walking ability. In addition to the key points summarized in chapters 4 and 5, some overall commentary can provide additional context to this work.

The existing literature, in addition to our study findings, certainly emphasizes the strong link between lower extremity motor function and walking ability in SCI. It is important however to acknowledge the differences in the strength of relationships between components of lower extremity motor function and walking. Furthermore, the studies by Waters (1994), Kim (2004), Scivoletto (2008) as well as the present study, each identify slightly different patterns of lower
extremity muscle groups that are most important for walking. These results emphasize the heterogeneity of incomplete SCI, and challenges in applying these findings at an individual patient level. Our results also emphasize the need to further examine the relationships of individual muscle groups to different components of walking ability in SCI and the patterns of recovery between different lower extremity muscle groups.

Considering our results and previous literature within the framework of the gait determinants in Figure 1 emphasizes the importance of further examining other factors which may influence walking ability in SCI. The majority of SCI literature to date has in fact focused primarily on lower extremity motor strength. Although our study did not identify a significant relationship between LEPS and walking measure, the role of sensory function particularly proprioception and sensory integration certainly warrants future study. Scivoletto (2008) recently found significant correlations between both balance and spasticity and walking ability. Given the nature of impairments following an incomplete SCI, further examination of these potential determinants would be valuable. In particular, there is a paucity of literature in the area of postural control and trunk muscle function in SCI and therefore very little is currently known about the influence of these factors on walking in SCI. Although the complexity of measuring postural control and trunk function has limited this line of inquiry, a better understanding of these factors is critical for the development of future SCI interventions. The examination of other gait determinants such as aerobic capacity and vision would also be valuable especially given the diversity in incomplete SCI in terms of age and other co-morbidities.

The present study incorporated a broader range of walking measures than has previously been used in a single study. Our results demonstrate the added value in using such a comprehensive group of walking measures. In particular, despite a small sample size, the present study illustrates that walking ability is not uniform across different measures since not all
subjects were able to complete all tests. In contrast, other studies such as Kim (2004) and van Hedel (2006) included only individuals who were able to perform all of the measures.

Another important consideration identified in the present study relates to the constructs of physical assistance, upper extremity, and lower extremity assistive device usage and whether these components should be integrated into one scale or considered as separate items. In choosing whether to utilize an integrated scale such as the WISCI-II or separate scales for physical assistance and assistive devices, it is important to consider the objectives of the intervention as well as the need for one discrete scale such as is the practice in clinical trials. Our results also re-iterate the recent findings by Ditunno (2008) and van Hedel (2008) regarding the regional practice variations particularly related to assistive device usage which must be considered when using measures involving these applications.

van Hedel et al. (2008) recently concluded that the 10mWT is best tool to measure walking capacity in SCI. Given the ease in administration, strong psychometric properties, and the ability to compare to normative values, these conclusions are warranted. However as previously discussed, further value can also be added to the 10mWT by examining the differential between preferred and maximal walking speeds in individuals with SCI (van Hedel, 2007). Although the 10mWT may be considered the ideal walking measure in SCI, our results also illustrate the value of TUG and 6MWT as well as the WMS as an overall measure of walking participation.

It is also valuable to consider how the walking measures used in the present study align with the Patla's model of community mobility presented in the theoretical framework in Figure 1. The walking measures used in our study and in the majority of SCI locomotion studies previously discussed are completed in a standardized indoor environment and potentially represent only a few environmental dimensions that constitute the requirements for community mobility.
mobility. In particular, the time constraints dimension may be represented by both the 10mWT and the 6MWT however it would be important to understand the time requirements for individuals or a particular community setting and then determine the walking speeds necessary to meet those time challenges. The distance walked during 6MWT may also be applied to the minimum walking distance requirement from the theoretical framework however it is important to recognize that this is a time-limited test which therefore will not capture the overall distance an individual could walk over unlimited duration. Another important dimension of community mobility is the ability to perform postural transitions. The TUG incorporates several postural transitions such as sit-to-stand, gait initiation, gait termination, and stand-to-sit. In the future however, it may be valuable to measure individual components of this test such as sit-to-stand in order to understand their influence on overall test performance. In addition to our TUG results, findings from Chang (2004) related to impairments in gait initiation in incomplete SCI, supports the need for further investigation and consideration of postural transitions for overall walking ability in SCI. Lajoie and colleagues (1999) have also identified that individuals with incomplete SCI have greater attentional requirements which is another important dimension of community mobility. With the exception of the WMS, the measures used in our study do not consider the contextual aspects of community walking and specifically the challenges of different ambient conditions, terrains, or traffic. Given the complex impairments of sensorimotor function and balance that result from SCI, future examination of the ability of individuals with SCI to walk under different environmental conditions would be highly relevant. Finally, the ability to manage external physical loads such as carrying an object or opening a door imposes additional stress on the postural control system (Patla, 1999). This dimension is very pertinent in SCI given the likelihood for bilateral extremity involvement and the potential for concomitant upper extremity and hand impairments however the ability to manage external
loads has not yet been studied. Musselman and Yang (2007) recently documented the walking task most commonly encountered during everyday life for able-bodied individuals and those with SCI and identified several tasks consistent with Patla’s environmental dimensions such as uneven terrains, carrying objects, and opening doors. Further examination of these tasks in individuals with SCI would provide valuable information regarding overall community mobility and could support the development of new interventions particularly relevant for community participation.

CHAPTER 6: Summary & Conclusions

The present study focused on understanding the relationships between sensorimotor function as measured by components of the ISCSCI clinical examination and a group of walking measures that have been validated in SCI within a cross-section of individuals with chronic, motor-incomplete SCI. Inherent in our study design are several limitations. In particular, the cross-sectional nature of the study limits any inferences regarding causal relationships. In addition, our study was comprised of a sample of convenience of individuals participating in the FES-walking trial. As such, the sample may have been biased towards individuals who were able to walk but not fully recovered as well as those individuals who were still highly motivated to pursue the goal of walking. Furthermore, since subjects were required to participate in an intervention three times a week for 12 weeks and also be available for ongoing follow-up for one year, the sample was comprised of individuals predominately living within the Toronto area who were available to attend sessions on an ongoing basis. This may partially account for the relatively older age of our subjects (mean=51.5 years, 22 – 77 years) since many of our participants were either retired or unemployed. Our study sample was also made up predominantly of individuals with tetraplegia (n=19/25) which may have had an impact on our
results. Finally, our small sample size \((n=25)\) limits the generalizability of our study findings. In particular, some of the conclusions drawn related to walking measures involved sample sizes of less than 15 (e.g. 6MWT and TUG). It is also important to acknowledge the limitations of the measure of sensorimotor function, the ISCSCI examination. Although widely used in clinical trials, the measure consists of a summation of ordinal scores and is restricted to specific muscle groups and sensory points associated with spinal nerve roots represented in the scale. As a result, other muscle groups such as the hip abductors, extensors, and knee flexors, not included in the ISCSCI but important for walking, were not examined in this study. Nonetheless, our findings highlight the value of studying relationships in a small but heterogeneous group including the examination of individual cases and the details that can be gained by such analysis.

In particular within the context of our theoretical framework, the present study identifies several opportunities for future study. As suggested in the manuscripts presented in chapters 4 and 5, several of our study findings would benefit from larger scale and/or longitudinal studies. Furthermore, using the presented theoretical framework as guide, several areas of future study can be identified. For example, the present study supported previous literature regarding the importance of lower extremity motor function for walking in SCI. However we now know that lower extremity strength is not the sole determinant of walking ability. In order to support the development of new rehabilitation interventions that specifically address the impairments that influence walking ability and to individualize current treatment approaches to optimize neuroplasticity, it is essential to understand the broad range of factors such as postural control and sensation that may also influence walking ability in SCI. Although significant progress has been made in the area of walking measures in SCI, future studies need to examine further the influence of different components of walking such as assistive devices and physical assistance, the effects of regional practice variations, and how these factors may influence study outcomes.
In addition, our study results as well as the theoretical framework emphasize the need to measure other components of walking ability such as sit-to-stand, other postural transitions as well as community mobility.

In conclusion, the present study has several important implications for SCI clinical practice and research. Our results demonstrate the importance of lower extremity motor function, both composite and individual muscle strength scores, for walking in SCI and identify a threshold LEMS level necessary for walking. Although important, lower extremity motor function is not the sole factor necessary for ambulation following a SCI. Our study highlights the importance of developing sensitive measures of sensation and postural control in order to better examine these potential relationships. Through the use of such a broad range of SCI walking measures, the present study has also revealed the variability in walking ability between individuals and between measures and the importance of capturing several components of walking such as assistive device usage, sit-to-stand ability, and community walking participation in addition to walking speed. Finally, our study provides a launching pad for several areas of inquiry research which could enable a more comprehensive understanding of the complex relationships between the determinants of walking and overall community walking mobility.
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### APPENDIX 1: Walking Index for SCI – Version Two (WISCI-II)

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Client is unable to stand and/or participate in assisted walking</td>
</tr>
<tr>
<td>1</td>
<td>Ambulates in parallel bars, with braces &amp; physical assistance of 2 persons, less than 10 meters</td>
</tr>
<tr>
<td>2</td>
<td>Ambulates in parallel bars, with braces &amp; physical assistance of 2 persons, 10 meters</td>
</tr>
<tr>
<td>3</td>
<td>Ambulates in parallel bars, with braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>4</td>
<td>Ambulates in parallel bars, no braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>5</td>
<td>Ambulates in parallel bars, with braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>6</td>
<td>Ambulates with walker, with braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>7</td>
<td>Ambulates with 2 crutches, with braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>8</td>
<td>Ambulates with walker, no braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>9</td>
<td>Ambulates with walker, with braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>10</td>
<td>Ambulates with one cane/crutch, with braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>11</td>
<td>Ambulates with 2 crutches, no braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>12</td>
<td>Ambulates with 2 crutches, with braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>13</td>
<td>Ambulates with walker, no braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>14</td>
<td>Ambulates with one cane/crutch, no braces &amp; physical assistance of 1 person, 10 meters</td>
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<tr>
<td>15</td>
<td>Ambulates with one cane/crutch, with braces &amp; no physical assistance, 10 meters</td>
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<td>Ambulates with 2 crutches, with no braces &amp; no physical assistance, 10 meters</td>
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<td>Ambulates with no devices, no braces &amp; physical assistance of 1 person, 10 meters</td>
</tr>
<tr>
<td>18</td>
<td>Ambulates with no devices, with braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>19</td>
<td>Ambulates with one cane/crutch, with no braces &amp; no physical assistance, 10 meters</td>
</tr>
<tr>
<td>20</td>
<td>Ambulates with no devices, no braces &amp; no physical assistance, 10 meters</td>
</tr>
</tbody>
</table>

APPENDIX 3: Battery of SCI Walking Measures

1) **FIM – L**: Level of physical assistance/independence (1 - 7)

2) **ASSISTIVE DEVICES SCORES**

   i. **UE AD SCORE (0 - 8)**
      - None: 4 4
      - Cane(s): 3 3
      - Quad cane, crutches (forearm/axillary): 2 2
      - Walker: 2
      - Parallel Bars: 0

   ii. **LE AD SCORE (0 - 6)**
      - None: 3 3
      - AFO: 2 2
      - KAFO: 1 1
      - RGO: 0 0

   iii. **TOTAL AD SCORE**
       Sum of UE & LE AD scores (0 - 14)

3) **WISCI-II**: Level of independence and assistive device usage (0 – 20)

4) **10-METRE WALK TEST** (m/s)

5) **TIMED UP & GO TEST** (seconds)

6) **SIX-MINUTE WALK TEST** (meters)

7) **WALKING MOBILITY SCALE (1 - 5)**

   1. **PHYSIOLOGIC AMBULATION**: Endurance, strength, or level of assistance required make ambulation not functional. May require assistance to stand. *(For exercise only)*
   2. **LIMITED HOUSEHOLD AMBULATION**: Able to walk in the home but limited by endurance, strength, or safety. *(Walks rarely in the home/never in community)*
   3. **INDEPENDENT HOUSEHOLD AMBULATION**: Walks continuously for distances that are considered reasonable for inside the home. May require assistance with stairs inside and curbs, ramps outside the home. A wheelchair may be used outdoors. *(Walks occasionally in home/rarely in community)*
   4. **LIMITED COMMUNITY AMBULATION**: A wheelchair may be used for long distances. *(Walks regularly in the home/occasionally in community)*
   5. **INDEPENDENT COMMUNITY AMBULATOR**: Walks for distances of approximately 400 m at speed at least half of normal. Can manage all aspects of walking safely, including curbs, stairs & doors. *(Walks regularly in the community & rarely/never uses wheelchair)*