Reactive Stepping Ability in Individuals with Incomplete Spinal Cord Injury

by

Katherine Chan

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Rehabilitation Sciences Institute
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Abstract

Up to 75% of individuals with incomplete spinal cord injury (SCI) experience at least one fall each year. Reactive stepping is one strategy used to prevent falls. Our objective was to describe reactive stepping ability of individuals with incomplete SCI compared to able-bodied adults. Forty-two individuals participated (17 with incomplete SCI). Participants adopted a forward lean position whilst attached to a rigid structure through a horizontal cable positioned at waist height. The release mechanism was unexpectedly triggered to elicit reactive stepping. Behavioural responses (i.e. single step, multi-step, fall) were significantly different between groups whereas movement timing of the stepping leg (i.e. step-off, step contact) was not significantly different. The onset of muscle activation was significantly slower for two lower extremity muscles in participants with SCI compared to able-bodied adults. Reactive stepping ability is likely impaired in individuals with incomplete SCI suggesting reactive balance control should be targeted in SCI rehabilitation.
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# Table of Contents

Acknowledgments ........................................................................................................ iii  
Table of Contents ........................................................................................................ iv  
List of Tables ................................................................................................................ vii  
List of Figures ............................................................................................................... viii  
Chapter 1 Introduction ............................................................................................... 1  
  1.1 Rationale for Study .............................................................................................. 1  
  1.2 Objectives of Study ............................................................................................ 3  
  1.3 Potential Impact of Study ................................................................................... 3  
Chapter 2 Literature Review .................................................................................... 5  
  2.1 What is spinal cord injury? .................................................................................. 5  
  2.2 Balance Control .................................................................................................. 6  
  2.2.1 Age Differences in Balance Control ................................................................. 8  
  2.3 Assessment of Reactive Balance ......................................................................... 9  
  2.4 Balance Control after SCI .................................................................................. 10  
  2.5 Falls and Fear of Falling after SCI ..................................................................... 12  
  2.6 Summary ............................................................................................................ 13  
Chapter 3 Methodology ........................................................................................... 14  
  3.1 Overview ............................................................................................................ 14  
  3.2 Participants ......................................................................................................... 14  
  3.2.1 Sample Size .................................................................................................... 15  
  3.3 Recruitment of Participants .............................................................................. 15  
  3.4 Study Procedures ................................................................................................ 16
List of Tables

Table 1. Demographics of the participants with incomplete SCI ........................................ 27

Table 2. Behavioural responses by group ............................................................................. 30

Table 3. Coefficient of variation of muscle activation timing for each muscle, by group ........ 34

Table 4. Timing of muscle activation by group ....................................................................... 35

Table 5. Foot-off timing, foot contact timing and swing duration by group ....................... 36
List of Figures

Figure 1: EMG electrode placement ................................................................. 17

Figure 2: Set-up of the lean-and-release test ...................................................... 19

Figure 3. Muscle activation pattern in a young able-bodied participant ............... 24

Figure 4. Muscle activation timing of the young able-bodied participants .......... 25

Figure 5. Muscle activation pattern in a matched able-bodied participant .......... 31

Figure 6. Muscle activation pattern in a participant with incomplete SCI .......... 32

Figure 7. Muscle activation pattern in a participant with incomplete SCI .......... 33

Figure 8. Muscle activation timing by group .................................................... 34

Figure 9. Percentage of single step responses compared to clinical measures ....... 38
Chapter 1
Introduction

1 Introduction

This study investigated the ability of individuals with incomplete spinal cord injury (SCI) to take a reactive step in response to a forward loss of balance while standing. A novel reactive balance measure, the lean-and-release test, was used to elicit reactive steps from individuals with SCI and able-bodied adults. Reactive balance responses, such as taking a step following an unexpected perturbation (i.e. slip or trip), are critical for fall prevention. The primary aim of this study was to describe the reactive stepping ability of individuals with incomplete SCI compared to age- and sex-matched controls. The components of a reactive step that were measured with the lean-and-release test included the behavioural response to the perturbation (i.e. single step, multi-step or fall), reaction timing (i.e. onset of electromyography (EMG) of six lower extremity muscles bilaterally), and movement timing (i.e. foot-off timing, foot contact timing, and swing duration). The findings suggest individuals with incomplete SCI have reduced reactive stepping ability as demonstrated by the higher occurrence of multi-steps and falls, suggesting a need to address reactive balance in SCI rehabilitation practice.

1.1 Rationale for Study

Up to three quarters of individuals with incomplete SCI experience at least one fall annually and most of these falls occur while walking (Amatachaya, Wannapakhe, Arrayawichan, Siritarathiwat, & Wattanapun, 2011; Brotherton, Krause, & Nietert, 2007; Wannapakhe, Arayawichan, Saengsuwan, & Amatachaya, 2014). However, predictors of falls in incomplete SCI are not well known (Phonthee, Saengsuwan, Siritaratiwat, & Amatachaya, 2013; Srisim, Saengsuwan, & Amatachaya, 2014), though there is evidence that balance during walking is compromised (Arora et al., 2018; Day, Kautz, Wu, Suter, & Behrman, 2012). Falls may result in injury and hospital admissions (Krause, 2004), leading to increased healthcare costs (Krueger, Noonan, Trenaman, Joshi, & Rivers, 2013; Munce et al., 2013).

One way to prevent a fall is to take a reactive step. Reactive stepping is imperative for recovering stability and preventing a fall following an unexpected perturbation; it involves taking one or more rapid steps after an unexpected loss of balance (Maki & McIlroy, 2006; Hollliday, Fernie,
Gryfe, & Griffs, 1990). Reactive steps serve to increase the size of the base of support (BOS) necessary for a balance-recovery reaction (Mansfield, Inness, Lakhani, & McIlroy, 2012). Following a forward loss of balance in a laboratory, measures of recovery by reactive stepping were found to be predictive of real-world forward falls (Carty et al., 2015). Poor reactive stepping is linked to falls for individuals with stroke (Mansfield, Inness, Wong, Fraser, & McIlroy, 2013) and older adults (Hilliard et al., 2008); however, it is unknown if and how reactive stepping ability is impaired in individuals with incomplete SCI and whether or not poor reactive stepping ability is related to falls in this population.

Although reactive stepping is important for balance recovery and fall prevention, it is not commonly assessed in clinical practice (Gervais et al., 2014; Sibley, Inness, Straus, Salbach, & Jaglal, 2013; Sibley, Straus, Inness, Salbach, & Jaglal, 2011), likely due to safety concerns and lack of standardization of its measurement. One component of the mini-Balance Evaluation Systems Test (mini-BESTest) assesses reactive stepping ability; however, as the measure uses a simple three-point ordinal scale for scoring (i.e. normal, moderate or severe), its ability to describe reactive stepping ability is likely limited.

The lean-and-release test was developed (Do, Breniere, & Brenguier, 1982) and recently used to evaluate reactive stepping for the stroke population (Lakhani, Mansfield, Inness, & McIlroy, 2011). This test simulates a forward fall in standing in which the individual is placed in a forward lean with approximately 10% body weight support from a horizontal cable attached at waist height from behind. The cable is released unexpectedly to trigger reactive stepping. The lean-and-release test is a safe and standardized test that provides quantitative data about reactive stepping ability, such as the timing of foot-off and foot contact and swing duration (Inness et al., 2015).

The aim of this research was to describe reactive stepping ability in individuals with incomplete SCI and identify whether their ability to take a reactive step is impaired relative to sex- and age-matched able-bodied controls. Reactive stepping ability of young (18-35 years old) able-bodied individuals, neither affected by age or an injury or disease, was also evaluated to establish reference values of the specific parameters investigated. The findings suggest that the reactive stepping ability of individuals with incomplete SCI is reduced compared to able-bodied individuals, as demonstrated by the greater number of multi-steps and falls.
1.2 Objectives of Study

Objective 1: To describe the reactive stepping ability of young able-bodied adults (aged 18-35 years), who are neither affected by age or condition, to establish reference values of the parameters investigated.

Objective 2: To describe the reactive stepping ability of individuals with incomplete SCI through use of the lean-and-release test. Specifically, to describe the behavioural response (i.e. single step, multi-step or fall), reaction timing (i.e. onset of EMG activation of six lower extremity muscles bilaterally), movement timing (i.e. timing of foot-off and foot contact and swing duration), and the relationship between the behavioural response and scores on clinical measures.

Due to the nature of the study being descriptive and exploratory, there is no hypothesis for these first two objectives.

Objective 3: To determine if and how reactive stepping ability of individuals with incomplete SCI differs from that of sex- and age-matched able-bodied controls and young able-bodied adults using the same parameters as listed in Objective 1.

Hypothesis (Objective 3): It was hypothesized that compared to able-bodied controls, individuals with incomplete SCI would 1) take more steps to regain balance and 2) have slower reaction (i.e. onset of EMG activation) and movement timing (i.e. foot-off and foot contact timing).

1.3 Potential Impact of Study

This study investigated the reactive stepping ability of individuals with incomplete SCI using a novel approach to reactive balance assessment. The lean-and-release test provides a behavioural and quantitative description of reactive stepping ability. The study findings have the potential to inform balance rehabilitation practice for individuals with incomplete SCI. First, the findings highlight how reactive stepping ability differs between individuals with incomplete SCI and able-bodied adults; there are few deficits in the timing of the reactive step, but there are differences in the behavioural response to the perturbation. Compared with able-bodied adults, individuals with SCI take fewer single steps to recover balance; more steps are needed to realign their extrapolated centre of mass (COM) within their BOS. This may suggest that during rehabilitation, the magnitude of the response (i.e. step length) should be targeted and trained
instead of the timing of the response. Second, the findings suggest that the behavioural response elicited by the lean-and-release test may be a useful outcome measure for ambulatory individuals with SCI who can take a step without any assistance. This thesis provides a greater foundational understanding of reactive balance in the incomplete SCI population, guiding future research and possibly leading to the standardization of a new reactive balance measure for those with SCI.
Chapter 2
Literature Review

2 Literature Review

This chapter reviews SCI, balance control, and the causes and consequences of falls in the SCI population. Deficits resulting from a SCI affect one’s ability to maintain stability while standing and walking, increasing the risk of falls and subsequent injuries. The importance of reactive balance is described here and the lean-and-release test, which has previously been used in stroke and older adult populations, is introduced as a reactive balance measure for incomplete SCI. There is a gap in our understanding of the deficits in reactive balance control in the SCI population; one of the aims of this study is to address the paucity of research on this topic.

2.1 What is spinal cord injury?

The spinal cord is the main circuit through which sensory and motor information travels between the brain and body (Maynard et al., 1997). A SCI disrupts conduction of sensory and motor signals at and below the level of injury (Maynard et al., 1997). Spinal cord injuries can be classified as either complete, defined as an absence of sensory and motor function more than three segments below the neurological level of injury, or incomplete where there is partial preservation of sensory and/or motor function below the level of injury (Maynard et al., 1997; Waters & Adkins, 1991). Incomplete injuries can further be divided into motor complete, in which some sensory but no motor function is preserved below the neurological level and includes the sacral segments, or motor incomplete, defined as preservation of some motor function below the neurological level (Maynard et al., 1997).

The American Spinal Injury Association Impairment Scale (AIS) is commonly used to classify SCI by evaluation of sensory and motor function above and below the neurological level of injury. An AIS grade of A represents a complete injury, while AIS grades B, C and D represent incomplete injuries. An AIS B SCI is a motor complete injury. An AIS grade of C is a motor incomplete injury with key lower extremity muscles receiving a grading less than three (i.e. the muscle cannot move through full range against gravity), whereas D is a motor incomplete injury with key lower extremity muscles receiving a grading of three or more. An AIS grade of E represents normal sensory and motor function (Maynard et al., 1997). In addition to the potential
loss of sensory and/or motor function, these individuals may experience deficits such as the inability to walk, loss of trunk control and loss of arm/hand function (Anderson, 2004). Individuals with motor incomplete SCI typically have some ability to stand and walk due to the sparing of some motor function below the level of injury (Burns, Gelding, Rolle, Graziani, & Ditunno, 1997). Impaired autonomic function, decreased bone density, and abnormalities in muscle tone (Craven et al., 2012) may also be experienced by individuals with SCI.

In North America, the incidence of SCI ranges from 27 to 47 cases per million (Fisher, Noonan, & Dvorak, 2006). While the incidence of SCI has been stable over the past 30 years the number of survivors has increased, resulting in a greater prevalence (Fisher, Noonan, & Dvorak, 2006). Further, the age of SCI onset has risen. According to a sample from the National SCI Database, the mean age of SCI has risen from 28.9 years (1973-1979) to 38 years (2000-2003) (Jackson, Dijkers, Devivo, & Poczatek, 2004). In Ontario, the average age at the time of injury was 51.3 years in 2010 (Couris et al., 2010). In Canada, increasing incidence of non-traumatic SCI alongside its aging population is the main cause for the increase in mean age of SCI onset (Noonan, Farry, Singh, Fehlings, & Dvorak, 2012). With more Canadians experiencing SCI, many of whom are older with pre-existing medical conditions, the need for effective rehabilitation services has never been greater.

2.2 Balance Control

Balance control, also known as postural control, is important during standing and walking in order to maintain stability and prevent falls. Balance is controlled by keeping the vertical projection of one’s COM (i.e. the average position of all parts of the body according to mass) within the BOS (i.e. area of support beneath a person or object, including points of contact) (Mathiyakom & McNitt-Gray, 2008; Pollock, Durward, & Rowe, 2000). A displacement of the extrapolated COM outside of the BOS requires a reactive response to regain control of the extrapolated COM (Mathiyakom & McNitt-Gray, 2008). There are two types of balance control: reactive (compensatory) and proactive (anticipatory) (Maki & McIlroy, 1997). Proactive balance is engaged to counteract predictable disturbances (i.e. volitional movement), whereas reactive balance is activated in response to an unexpected perturbation (i.e. slip or trip) (Maki & McIlroy, 1997). Proactive balance requires higher executive function for the selection and planning of adaptive movements, involving cortical control and sensory inputs (Misiaszek, 2006). However,
reactive balance occurs more automatically and does not involve higher executive functions (Misiaszek, 2006).

When encountering an unexpected perturbation, the reactive balance strategy used is dependent on the size of the perturbation. For smaller perturbations, in-place responses (i.e. ankle or hip strategy) are sufficient to regain balance (Horak & Nashner, 1986). For larger perturbations, change-in-support responses (i.e. stepping or reaching and grasping) are necessary (Maki & McIlroy, 1997). During change-in-support responses, spatial characteristics (e.g. limb trajectory) and the timing of response initiation and execution (i.e. latency and speed) are both critical for controlling the motion of the extrapolated COM (Maki & McIlroy, 1997).

Reactive stepping is crucial for recovering stability and preventing falls following an unexpected perturbation (Do et al., 1982). Reactive stepping involves taking one or more rapid steps after an unexpected loss of balance (Maki & McIlroy, 2006; Hollliday, Fernie, Gryfe, & Griffis, 1990). Reactive steps increase the size of the BOS which is essential for balance-recovery reactions (Mansfield, Inness, Lakhani, & McIlroy, 2012). These reactive steps are characterized by complex factors such as extremely rapid onset and movement speed (McIlroy & Maki, 1996), amplitude and trajectory scaled to the degree of instability (McIlroy & Maki, 1993), and the ability to accommodate environmental circumstances (Zettel, McIlroy, & Maki, 2002). A distinguishing feature of a reactive step is the absence of anticipatory postural adjustments that occur after the perturbation, but before the onset of the compensatory step (McIlroy & Maki, 1995). In a study that compared the initial response following a platform-translation perturbation to subsequent trials, an anticipatory phase involving weight acceptance through the stepping leg was observed in many of the subsequent trials, but not the initial trial (McIlroy & Maki, 1995). Inclusion of this phase of anticipatory postural adjustment did not appear to affect the timing of the stepping movement itself in this study involving young able-bodied participants (McIlroy & Maki, 1995).

Balance control is a complex motor skill that involves the synchronous activation of several sensorimotor processes. Orientation and equilibrium are two components that contribute to balance control. Orientation is the active control of body alignment and tone in relation to gravity, support surface, visual environment and internal references (Horak, 2006). Equilibrium is the coordination of sensorimotor systems to maintain the body’s COM during self-initiated
and external perturbations in postural stability (Horak, 2006). Global measures of balance are insufficient to determine deficits and impairments in differing environments and scenarios that result in the failure of one’s postural control (Horak, 2006). There is need for a more comprehensive evaluation of balance strategies and impairments underlying the functional performance of postural stability to guide balance rehabilitation and fall prevention (Horak, 2006).

The original Systems Framework of Postural Control consisted of six essential components of balance control: biomechanical constraints (i.e. degrees of freedom, strength, limits of stability); cognitive processing (i.e. attention, learning); movement strategies (i.e. reactive, anticipatory, voluntary); control of dynamics (i.e. gait, proactive); sensory strategies (i.e. sensory integration and reweighting); and orientation in space (i.e. perception, gravity, surfaces, vision) (Horak, 2006). Sibley and colleagues have since expanded this framework to include nine components, one of which is reactive postural control (Sibley, Beauchamp, Van Ootegehm, Straus, & Jaglal, 2015). Reactive balance was likely added to emphasize its importance for recovery of stability and fall avoidance (Maki & McIlroy, 1996). Poor reactive stepping is linked to falls in populations such as stroke (Mansfield, Inness, Wong, Fraser, & McIlroy, 2013) and older adults (Hilliard et al., 2008); however, whether reactive stepping ability is related to falls in individuals with SCI is unknown. This study focuses on the movement strategies component of the Systems Framework of Postural Control, specifically reactive balance.

2.2.1 Age Differences in Balance Control

Age-related factors exist that may affect balance control. Several studies have found an age-related reduction in voluntary muscle strength (Brown, Shumway-Cook, & Woollacott, 1999; McIlroy & Maki, 1993; Pai, Rogers, Patton, Cain, & Hanke, 1998) and rate of muscle force production (Clarkson, Kroll, & Melchionda, 1981; Hakkinen & Hakkinen, 1991), affecting the magnitude and firing rate of counterbalancing muscles necessary for postural control (Jensen et al., 2001). With respect to reactive stepping, the timing and scaling of step initiation are typically similar in young and older adults (Luchies, Wallace, Pazdur, Young, & DeYoung, 1999; Maki & McIlroy, 1997; Thelen, Wojcik, Schultz, Ashton-Miller, & Alexander, 1997). It has even been found that some older adults may step earlier than young adults to reduce the risk of losing their balance (McIlroy & Maki, 1996). Studies investigating the stepping response following an
anteroposterior perturbation have shown that older adults tend to initiate stepping at lower levels of instability compared to young adults (Jensen et al., 2001; Mille et al., 2003). The differences in reactive stepping ability due to age are primarily associated with control of the swing phase and landing, rather than step initiation (Maki & McIlroy, 2006). The maximum stepping speed of older adults is slower compared to that of young adults, which limits the ability of older adults to recover from falls (Thelen et al., 1997). Older adults experience more difficulty during stepping reactions due to a greater tendency to take multiple steps (Luchies, Alexander, Schultz, & Ashton-Miller, 1994; McIlroy & Maki, 1996; Wolfson, Whipple, Amerman, & Kleinberg, 1986), the necessity to initiate arm reactions (McIlroy & Maki, 1996) and the failure to recover equilibrium (Pavol, Runtz, Edwards, & Pai, 2002). In addition, older adults have longer reaction times, slower flexion and extension velocities of the swing limb, and shorter step lengths (i.e. shorter BOS) (Mathiyakom & McNitt-Gray, 2008). These factors hinder the execution of a successful stepping reaction following a perturbation.

2.3 Assessment of Reactive Balance

Reactive stepping ability is essential for fall prevention (Mansfield, Wong, Bryce, Knorr, & Patterson, 2015), but it is not commonly assessed in clinical practice (Gervais et al., 2014; Sibley, Inness, Straus, Salbach, & Jaglal, 2013; Sibley, Straus, Inness, Salbach, & Jaglal, 2011), likely due to safety and standardization concerns of its measurement. Recently, Mansfield and colleagues (2011) used the lean-and-release test to evaluate reactive stepping for the stroke population (Inness et al., 2015). The lean-and-release test simulates a forward fall in standing; the individual is placed in a forward lean with approximately 10% of his/her body weight supported through a horizontal cable attached at waist level from behind and the cable is suddenly released, triggering reactive stepping. The lean-and-release test is a safe and standardized test that provides quantitative data about reactive stepping ability (Inness et al., 2015). In addition, the lean-and-release test has been successfully incorporated into hospital settings (Inness et al., 2015). Measures of recovery from forward loss of balance by stepping were found to be predictive of real-world falls and forward falls in particular (Carty et al., 2015).

Individuals with stroke have different reactive stepping patterns compared to able-bodied adults. Individuals with stroke show ineffective step responses, such as steps with inadequate foot clearance or complete absence of a step attempt (Lakhani et al., 2011; Mansfield et al., 2011,
2012). Individuals with stroke who are considered non-fallers have slower foot-off timing compared to healthy individuals (Lakhani et al., 2011; Mansfield et al., 2013); additionally, individuals with stroke who are fallers (i.e. those more likely to fall) present with an even a greater delay (Mansfield et al., 2013). Reactive stepping using the lean-and-release test has never been investigated in individuals with SCI, but one might expect to see slower initial step timing comparable to individuals with stroke and slower swing duration similar to older adults.

Recently, there have been several studies investigating the stepping response and balance control amongst different populations including SCI, stroke, older adults and individuals with knee osteoarthritis. The methods of perturbation used in these studies include pulls, lean-and-release, induced falls, treadmill-induced slips, and a walkway with a built-in slip device (Arora et al., 2018; Bair, Prettyman, Beamer, & Rogers, 2016; Fujimoto, Bair, & Rogers, 2017; Honeycutt, Nevisipour, & Grabiner, 2016; Hunt, Odle, Lombardo, Audu, & Triolo, 2017; Levinger et al., 2016; Salot, Patel, & Bhatt, 2016; Schinkel-Ivy, Huntley, Inness, & Mansfield, 2017; Street & Gage, 2017). Force plates, accelerometers and motion capture were common data collection tools; though, only one of these studies collected and analyzed EMG to measure onset of muscle activity (Arora et al., 2018). Among most of these studies, the earliest time point identified in the reactive response was the step lift-off or unloading of the stepping limb. In addition, most of these studies did not include analysis of the onset of EMG activity prior to the movement response (i.e. step lift-off).

2.4 Balance Control after SCI

A SCI may lead to impairments and deficits that affect control of balance. Injury to the central nervous system may result in a delayed onset of postural responses, inadequate scaling of motor responses, or inappropriate muscle firing patterns (Mummel et al., 1998). These deficits lead to a reduction in postural steadiness during quiet standing (Lemay et al., 2013). Quiet standing is maintained by the integration of somatosensory, visual and vestibular systems (Nashner, 2009). Following a SCI, somatosensory impairments may lead to a greater reliance on the visual system (Lemay et al., 2013). In addition, previous research involving individuals with incomplete SCI has shown a slower onset of EMG activity in the ankle muscles following a backward surface translation (Thigpen et al., 2009). This slower EMG activity likely also affects balance control.
Similar to standing, individuals with SCI have deficits in balance control during gait initiation and walking compared to able-bodied controls. Day and colleagues (2012) found greater variability in step width, step length, margin of stability, and anteroposterior and mediolateral foot placement while walking on a treadmill compared to able-bodied individuals (Day et al., 2012). Significant inverse relationships were found between standardized balance measures and gait variability, suggesting that higher balance assessment scores correlate with lower variability in spatial parameters or foot placements during walking (Day et al., 2012).

Following a SCI, individuals may experience abnormal movement patterns that affect their postural orientation and equilibrium. Individuals with incomplete SCI may have an insufficient recruitment of motor units when attempting to perform a movement, while exceeding normal levels of recruitment for other movements (Fong et al., 2009). This impairment in motor unit recruitment can inhibit planned movement required for maintaining one’s balance (Fong et al., 2009). Postural control following a SCI can also be affected by loss of muscle function. Muscles that function as extensors, primarily involved in weight support and propulsion and have the highest daily activity levels, are the most affected after the injury (Fong et al., 2009). Consequences of a SCI may affect one’s ability to maintain stability following an unexpected perturbation whether an in-place response or change-in-support response is required.

Animal models have been used to acquire a better understanding of the effects of SCI in humans. In one animal model, it was discovered that SCI has a severe impact on the muscle phenotype, such that there is a general shift toward an increase in the percentage of fibers having a faster phenotype within the affected muscles (Talmadge, 2000). In effect, the muscles below a spinal cord lesion become smaller, weaker, and more fatigable after the injury (Fong et al., 2009). Similar effects are generally observed in humans after SCI: atrophy, loss of maximum force potential, slow-to-fast fiber type conversion, and increased fatigability (Burnham et al., 1997; Castro et al., 1999; Gerrits et al., 1999; Shields, 1995). Chronic cases of SCI may lead to progressive decline in muscle function, further affecting balance control (Fong et al., 2009). In addition, the sensory impairments associated with SCI frequently result in decreased balance control. Following a SCI, an individual may incur a loss of sensation, specifically pain, temperature, and/or light touch (Nesathurai, 2013). Sensorimotor deficits may create perilous walking conditions with an increased risk of falls (van Hedel, Wirz, & Dietz, 2005). Numerous
factors may affect the capability of an individual with incomplete SCI to control their balance, especially in cases when reactive balance is required to prevent a fall.

Although there has been little study of reactive stepping ability in the SCI population, studies that have examined motor control during walking in individuals with SCI may provide some insight into the likely deficits in the stepping response. Impaired muscle coordination and co-activation (i.e. activation of both agonist and antagonist muscles) affects overground walking in individuals with incomplete SCI (Hayes, Chvatal, French, Ting, & Trumbower, 2014). EMG patterns for incomplete SCI are different to that of able-bodied and uninjured controls during treadmill walking (Gorassini et al., 2009). Individuals with incomplete SCI showed similar muscle activation patterns in their tibialis anterior and soleus; however, activation of the rectus femoris and biceps femoris were much greater compared to the able-bodied controls (Gorassini et al., 2009). There was also a greater amount of co-contraction in the tibialis anterior/soleus and biceps femoris/rectus femoris muscles compared to that in controls (Gorassini et al., 2009). These differences of EMG patterns found in individuals with incomplete SCI may translate into slower step initiation and poorer reactive stepping ability compared to able-bodied controls.

2.5 Falls and Fear of Falling after SCI

A consequence of impaired balance is falls, which are a common occurrence within the incomplete SCI population. Each year, approximately 75% of individuals with incomplete SCI experience at least one fall and most falls occur while walking (Amatachaya et al., 2011; Brotherton et al., 2007; Wannapakhe et al., 2014). Falls result in injury and hospital admissions (Krause, 2004) that lead to increased healthcare costs (Krueger et al., 2013; Munce et al., 2013). Therefore, fall prevention strategies are essential to minimize these outcomes.

Among individuals with incomplete SCI, the factors associated with a risk of falling are: living alone; obtaining a high school level of education or higher; having tetraplegia; having an AIS C classification (compared with AIS D classification); requiring a walking device; engaging in physical activity; and having a fear of falling (FOF) (Matsuda, Verrall, Finlayson, Molton, & Jensen, 2015; Phonthee et al., 2013). Individuals with higher functional ability are more likely to perform daily activities concurrently with walking and this ultimately increases their risk of falls (Phonthee et al., 2013). However, physical performance predictors of falls in incomplete SCI are not well known (Phonthee et al., 2013; Srisim et al., 2014); though there is evidence that balance
during walking is compromised (Arora et al., 2018; Day, Kautz, Wu, Suter, & Behrman, 2012). Similarly, increased engagement in physical activity is associated with falling (Matsuda et al., 2015).

Falls often contribute to a FOF; alternatively FOF can develop in absence of a fall (Friedman, Munoz, West, Ruben, & Fried, 2002). A FOF is often defined as “a lasting concern about falling causing one to avoid or curtail activities one felt they were capable of doing” (Brouwer, Musselman, & Culham, 2004). FOF has been shown to influence balance and gait control in older adults (Schinkel-Ivy, Inness, & Mansfield, 2016). Compared to older adults with no FOF, those with FOF demonstrate greater centre of pressure amplitude during eyes-closed quiet standing (Maki, 1991) and decreased lower limb strength (Brouwer et al., 2004). FOF may be a predictor for loss of balance or fall risk; however, little is known about FOF in individuals with SCI. A recent study of involving those with incomplete injuries found that 50% of the sample reported a fear of falling (Shah, Oates, Arora, Lanovaz, & Musselman, 2017). One study of male individuals with paraplegia found that post-injury FOF can affect postural control and rehabilitation potential (John, Cherian, & Babu, 2010). Fear of falling is just one factor that contributes to fall risk in individuals with incomplete SCI.

2.6 Summary

The consequences of a fall can have significant personal and economic costs (Krueger et al., 2013). Falls have become a growing concern for the incomplete SCI population (Amatachaya et al., 2011). Because of this, there is an increasing demand to understand the nature of balance deficits after SCI and establish tools to identify these deficits. Many factors should be considered for incomplete SCI rehabilitation in regards to balance, but one of particular interest is reactive balance as there is a paucity of research investigating this topic. There is cause to explore reactive stepping ability for individuals with incomplete SCI and consider the lean-and-release test as a measure of reactive balance. This exploratory study described the reactive stepping ability of individuals with incomplete SCI and determined whether or not there are differences in reactive stepping ability between this patient population and able-bodied controls. Improved health outcomes and decreased long-term costs of a SCI will result from a reduction in falls and fall-related injuries.
Chapter 3
Methodology

3 Methodology

3.1 Overview

This study used a prospective cross-sectional case-control design with a quantitative approach. As reactive balance has not previously been investigated in the SCI population, data of young able-bodied individuals were collected and used as a reference. Data from participants with incomplete SCI were compared to data from age- and sex-matched able-bodied controls in order to identify differences in reactive stepping ability on the lean-and-release test. Data for each participant were collected during one session that lasted approximately 1.5-2 hours. All data were collected at the Lyndhurst Centre, Toronto Rehabilitation Institute – University Health Network (TRI-UHN). This study was approved by the UHN Research Ethics Board (REB).

3.2 Participants

Individuals with incomplete SCI were recruited based on the following inclusion criteria: (1) ≥18 years old; (2) >12 months post-injury (chronic stage at the plateau of natural recovery) (Waters, Adkins, Yakura, & Sie, 1994a; Waters, Adkins, Yakura, & Sie, 1994b); (3) AIS C or D; (4) traumatic or non-progressive non-traumatic cause of SCI; (5) moderate level of trunk control (i.e., score of ≥2 on the Berg Balance Scale Reaching Forward Task; the ability to reach forward >5 cm with an outstretched arm in standing) (Berg, Wood-Dauphinee, & Williams, 1995); (6) ability to stand independently for at least 30 seconds with no assistance; and (7) free of another condition besides their SCI that affected balance or walking (e.g., stroke, vision loss, vestibular disorder). Alternatively, individuals with incomplete SCI were excluded based on the following criteria: (1) severe spasticity and/or contractures in the lower extremity that prevented the individual from maintaining an upright position; (2) a pressure injury, greater than a grade 2, on the pelvis or trunk where the harness was donned; and (3) a history of a lower extremity fragility fracture, indicating decreased bone density.

Able-bodied participants were recruited based on the following inclusion criteria: (1) no diagnosis of a condition or injury that affected balance or walking; (2) no history of a lower extremity fragility fracture; and (3) ability to independently ambulate without a walking aid
and/or an ankle-foot orthosis. Young able-bodied participants were 18-35 years of age, while the able-bodied controls were sex- and age-matched (±3 years) to the participants with SCI.

Informed consent was obtained from all participants prior to enrollment in the study. Questions and concerns were addressed before a signature was obtained. Interpretation was provided for participants whose first language was not English. Consent documentation and procedures approved by the UHN REB were used and followed.

3.2.1 Sample Size

Reactive stepping ability had not previously been investigated for the incomplete SCI population. Therefore, data from young healthy adults (Lakhani et al., 2011) and individuals with stroke (Mansfield et al., 2013) were used for the sample size calculation for an independent samples t-test. Movement timing of the reactive step (i.e. timing of foot-off) was used with an alpha of 0.05 and a power of 0.8, resulting in 13 participants per group (Portney & Watkins, 2011). The recruitment target of individuals with incomplete SCI was 20 to account for withdrawal from the study for various reasons (e.g. fear of falling in forward lean position).

3.3 Recruitment of Participants

Flyers were mailed to outpatients of the Lyndhurst Centre TRI-UHN who had previously consented to being contacted by research personnel regarding study involvement. Recruitment flyers were posted on bulletin boards throughout the Lyndhurst Centre. Interested participants were screened over the phone by a study investigator to confirm their eligibility for the study. If the participants seemed eligible, they came in-person to be evaluated by a study investigator, who evaluated whether they could stand independently for at least 30 seconds, reach forward in standing, and whether or not they had spasticity or contractures that affected their ability to stand upright.

Young able-bodied individuals and sex- and age-matched controls were recruited through word of mouth by the research team. In addition, an email was sent to all members of the Neural Engineering and Therapeutics Team at the Lyndhurst Centre.
3.4 Study Procedures

3.4.1 Demographics

The following demographic information were collected from all participants at the testing session: birth month and year, sex, weight, and the number of falls experienced in the past three months. A fall was defined as coming to rest on the ground or other lower surface unintentionally (World Health Organization, 2018). Additional information was collected from the participants with incomplete SCI, including: AIS score, neurological level of injury, time post-injury (months), cause of SCI, whether or not they relied on a gait aid for daily ambulation, and whether they could independently initiate a step. Participants with SCI were also asked if they had a fear of falling, defined as a lasting concern about falling resulting in avoidance or curtailing of activities despite being capable of doing them (Brouwer et al., 2004).

3.4.2 Data Acquisition Equipment

Surface EMG (Delsys Inc., Natick, MA, USA) recorded the timing of muscle activation in six muscles of the lower extremity bilaterally: rectus femoris (RF), biceps femoris (BF), vastus lateralis (VL), tibialis anterior (TA), medial gastrocnemius (MG), and soleus (SOL) (Figure 1). EMG electrodes were placed just proximally to the middle of the muscle belly in parallel to the muscle’s fibre direction. A ground electrode was placed on a bony landmark, the patella, where the least amount of subcutaneous tissue was found. Hair was shaved and skin was rubbed with alcohol in order to minimize the impedance of the EMG signal. All EMG leads were placed while the participant was in a seated position. The EMG signals were amplified by 1000 (Delsys Inc., Natick, MA, USA). All analog data were collected at a frequency of 2000 Hz using PowerLab DAQ (ADInstruments Inc., Colorado Springs, CO, USA) and Lab Chart 7 (ADInstruments Inc., Colorado Springs, CO, USA).

Four force plates (Advanced Mechanical Technology Inc., Watertown, USA) measuring 251 x 502 mm were oriented such that two adjacent force plates were positioned anteriorly to the other two adjacent force plates (posterior force plates) (Figure 2). Participants stood on the two posterior force plates (i.e. one foot on the right force plate and one foot on the left force plate) while foot contact was recorded using all four force plates depending on the step length of the participants. A force transducer allowed for live visual feedback of the body weight support.
through the horizontal cable. Analog signals from the force plates and force transducer were amplified and converted analog-to-digital (A/D) using a 16-bit A/D card (National Instruments, Austin, TX, USA) (± 5 volts input range). The force plates were placed into a wooden platform, creating a flat surface in the collection area. A ramp allowed for safe maneuvering into and out of the collection area. Motion capture (Vicon, Culver City, CA, USA) was collected using 40 reflective markers on various landmarks of the body; however, these data were not used in this thesis.

![Figure 1: EMG electrode placement. Anterior (left) and posterior (right) aspects of surface EMG electrode placements. Each pair of markers represents the two electrodes, with a 2-cm inter-electrode distance, per lead.](image)

### 3.4.3 Collection Procedure

Following application of the EMG electrodes, the participant donned a safety harness (Robertson Harness, Ft. Collins, CO, USA) consisting of one pelvis, one chest and two leg straps. The ceiling attachment to which the harness was fastened had been weight-tested to support up to 150 kg. EMG wires were then taped to the harness or the participant’s clothing to minimize artifact while ensuring that the wires would not interfere with the participant’s ability to take a step. The participant was then asked to enter the collection area and body weight was recorded with two of
the force plates. The measure of body weight was used to establish the 8-12% body weight support threshold through the cable during the forward lean. A cable was fastened to a handle on the safety harness at waist height and the other end was attached to a release mechanism that was built by an engineer of our research team. The height of the release mechanism was adjusted according to the participant’s height to ensure that the horizontal cable was parallel to the floor. To induce leaning, participants were given the following instructions: “The harness is fastened to a cable behind you; try your best to lean forward from the ankles, not the hips. Your goal is to reach 10% body weight support through the cable, so we will let you know if you need to lean more or less, or if you need to move your feet forward or backward. Try to distribute your weight evenly between your feet. Upon release of the cable, do your best to recover your balance in order to prevent a fall. In the event that you do lose your balance, the harness and ceiling attachment will bear your full weight and you will also receive physical assistance from one of the research team members.” A research team member also demonstrated how to lean from the ankles and how to incorrectly lean by flexing at the hip (Figure 2).

The body weight support threshold was chosen to control for the variability in dorsiflexion or lean angle. For participants that were not able to reach the target threshold, the lean-and-release was still conducted at the body weight support they were able to reach and this was documented in the data collection notes. Up to ten lean-and-release trials were conducted, as tolerated by the participant. Trials were ceased if participants mentioned experiencing fatigue or discomfort. Three false trials (i.e. mechanism was not released) were included, resulting in a target of 13 trials in total, and trials were randomized in an attempt to minimize the engagement of proactive balance strategies. Participants were unaware of the number of release or false trials to minimize anticipation of remaining trials.

During the lean-and-release test, behavioural data were collected. Stepping reactions were classified as single step, multi-step or fall. A single step was identified as a single foot being lifted off the floor with a single foot contact. A multi-step reaction was identified as a single foot being lifted off the floor, a single step being taken, followed by at least one more step of the same or opposite foot. A fall was classified as the inability to recover balance without external assistance from the harness or a researcher. The leg that initiated the first step was referred to as the stepping leg while the other leg was referred to as the supporting leg. This behavioural outcome was collected due to its clinical feasibility as it only required researcher observation.
The parameters of interest, expressed relative to the timing of the release, were (1) onset of EMG activation in six lower extremity muscles in each of the stepping and supporting legs; (2) foot-off timing of the stepping leg (i.e. indicated when one force plate signal showed <1% body weight support) and (3) foot contact timing of the stepping leg (i.e. indicated when one force plate signal showed >1% body weight support). The timing of release was identified as the point in time when the force transducer signal indicated that <1N of weight was being supported through the cable. Swing time was also analyzed, calculated as the time difference between foot-off and foot contact of the stepping leg. Any adverse events that occurred during the testing sessions were documented (i.e. irritation of the skin, injuries, falls).

Participants with incomplete SCI completed two testing sessions spaced two weeks apart. The first testing session was treated as a familiarization session. Data from the second testing session were analyzed and reported.

Figure 2: Set-up of the lean-and-release test. An example of a participant with SCI in the lean position prior to the release of the cable (left). Participants were encouraged to lean at the ankle joint but this was not always achieved, as shown here. On the right, an example of a young able-bodied participant in the “lean” position. In most cases, able-bodied individuals were able to lean from the ankles.
3.4.4 Clinical Measures

A licensed physical therapist conducted assessments of muscle strength and balance on participants with incomplete SCI. Muscle strength was graded on an ordinal scale of 0-5 using the manual muscle test (Yang et al., 2011). Twelve muscles bilaterally were assessed and the summative score, out of a possible total of 120, was used to describe lower extremity strength of the participants with incomplete SCI. The mini-BESTest evaluates four balance control systems, including a reactive component (Franchignoni, Horak, Godi, Nardone, & Giordano, 2010; King, Priest, Salarian, Pierce, & Horak, 2012; Leddy, Crowner, & Earhart, 2011; Lemay et al., 2013; Tsang, Liao, Chung, & Pang, 2013; Verrier, Gagnon, Musselman, et al., 2014). This scale has previously been used in SCI (Lemay et al., 2013; Shah et al., 2017; Verrier et al., 2014) and has been validated in SCI (Jorgensen, Opheim, Halvarsson, Franzen, & Roaldsen, 2017). Self-selected walking speed and step length were collected using the Zeno Walkway (ProtoKinetics LLC, Havertown, PA, USA). Participants walked two lengths of the Zeno Walkway without gait aids, if possible (braces permitted).

3.5 Data Analysis

Demographic and injury-related data were collected and reported in table format, using mean and standard deviation or frequency count. Behavioural responses were reported as a percentage of trials since not all participants were able to complete ten trials.

Offline processing was performed in MATLAB v. 2014a (MathWorks, Natick, MA, USA) using custom-written codes. Force plate and force transducer data were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 4 Hz. EMG data were full-wave rectified.

To detect the onset of EMG activation, an integrated protocol algorithm adapted from previous work was used (Allison, 2003; Santello & McDonagh, 1998). The average of the entire signal was calculated, including the period of inactivity prior to the release and the period of EMG activation during the reactive stepping. The algorithm integrated the difference between the rectified signal and the average value. The integrated signal decreased in amplitude until the onset of EMG activity, where the amplitude increased. The algorithm defined the lowest point of the integrated difference signal as the onset of EMG activity. Each EMG plot was then manually checked by one researcher (KC) to confirm or revise the automatically detected onset point. In
some cases, there was no distinct point of EMG onset; therefore, those EMG plots were rejected and no EMG onset output was provided for those muscles. Of the 456 EMG mean onsets across all participants, 27 (5.9%) were rejected. EMG traces of each trial for all muscles were overlaid for each participant to visualize the consistency or variability of the reactive stepping pattern across trials. To describe the variability, the coefficient of variation (CV) was calculated for each participant’s EMG onset for each muscle of the lower extremity.

Reaction and movement timing of single step responses were compared to the first step of a multi-step response to determine if there was a significant difference between the type of response. A Shapiro-Wilks test was used to determine normality of the reaction and movement timing of both types of responses. Independent samples t-tests were used for non-significant results (i.e. normal distributions) and Mann-Whitney U tests were used for significant results (i.e. non-normal distributions).

A Chi-square test was used to compare behavioural responses (single step vs non-single step) between groups. Behavioural responses were collapsed into a binary measure as this is what has been previously used in other clinical research studies (Mansfield, Peters, Liu, & Maki, 2010).

The EMG onset data and the CVs of the EMG onset data were analyzed with the Shapiro-Wilks test to assess normality. For non-significant results, these data were interpreted as having a normal distribution. As such, we performed independent samples t-tests on these data. Significant results identified non-normal distributions; therefore, we performed the non-parametric Mann-Whitney U test on these data.

The Shapiro-Wilks test was used to determine normality of the movement timing components. With non-significant results, these data were interpreted as normal and we proceeded to conduct independent samples t-tests, which were used to compare foot-off timing and foot contact timing relevant to the release point as well as swing time between groups.

The relationships between the percentage of single step responses with the dichotomous variables of fear of falling (presence or absence) and fall history (faller or non-faller) were evaluated using the Spearman correlation coefficient (ρ). The relationships between the percentage of single step responses with the scores of lower extremity strength, mini-BESTest scores, gait speed, and step length were evaluated using the Pearson correlation coefficient (r).
The magnitude of the correlation coefficients determined the strength of the correlation. A correlation coefficient (\( \rho \) or \( r \)) ranging between 0-0.39 was considered weak, 0.4-0.59 was considered moderately strong, and 0.6 or greater was considered strong (Evans, 1996).

Alpha was set to 0.05 for all statistical tests. The Bonferroni correction was used for all post-hoc analyses. All statistical analyses were performed on SPSS v.25 (IBM, Armonk, NY, USA).
Chapter 4
Results

4 Results

4.1 Young Able-bodied Participants

4.1.1 Demographics

Thirteen young able-bodied participants (6 females, 7 males) with a mean age of 24.5 ± 5.1 years (range 18-35 years) were enrolled in the study. None of the participants had previous exposure to the lean-and-release test. One participant (male, 24 years old) had experienced a fall in the previous three months when he tripped on a dumbbell at a fitness gym.

4.1.2 Behavioural Responses

Each young able-bodied participant performed ten lean-and-release trials resulting in a total of 130 trials. One participant (male, 26 years old) was able to recover their balance without taking a reactive step for two trials; this may have occurred due to the use of a hip strategy as opposed to leaning from the ankles. These two trials were excluded from data analyses. Out of 128 stepping reactions, 72.3 ± 41.9% were single step and 27.7 ± 41.9% were multi-step (Table 2). No falls were recorded for the young able-bodied group. Six participants (46.2%) always stepped with the same leg to perform the stepping response. It was observed that three participants (2 females, 1 male) attempted to delay step initiation by leaning into their toes before taking a reactive step.

4.1.3 Electromyography Onset

Most able-bodied participants showed a consistent pattern of EMG activation (Figure 3). Typically, the stepping and supporting SOL were activated first, followed immediately by the supporting and stepping MG. These onsets of muscle activity likely corresponded with body weight being transferred to the supporting leg while the stepping leg initiated a step by pushing off with the plantarflexors. The supporting TA and stepping BF were then activated, interpreted as more weight was transferred into the supporting leg and the stepping knee flexed for foot-off, respectively. This activity was followed by the onset of activity in the stepping TA for toe clearance and activity onset in the supporting BF and supporting RF. The stepping RF was
activated to achieve hip flexion just before the supporting VL and stepping VL for knee extension (i.e. swing through of the stepping leg) (Figure 4).

**Figure 3.** Muscle activation pattern in a young able-bodied participant. The average activation pattern of the muscles of the stepping (left plots) and supporting (right plots) legs for a young able-bodied participant (LR17, male, 27 years old) over ten trials. Time at 0 seconds signifies the point of release, the first vertical line (in red) identifies the average onset of EMG activation, the second vertical line (in blue) identifies the average foot-off timing and the third vertical line (in black) identifies the average foot contact timing over trials.
Figure 4. Muscle activation timing of the young able-bodied participants. The muscles are plotted in order of activation; the first six muscles are of the stepping leg and the latter six are of the supporting leg. Error bars reflect the standard deviation of each mean value.

4.1.4 Movement Timing

The mean foot-off timing for the young able-bodied participants was 368 ± 68 ms, the mean foot-off timing was 534 ± 91 ms, and the average swing duration was 167 ± 43 ms.

4.2 Able-bodied Matches and Participants with Incomplete SCI

4.2.1 Demographics

4.2.1.1 Able-bodied Matches

Twelve able-bodied individuals (9 females, 3 males) were sex- and age-matched (± 3 years) to the participants with incomplete SCI. The mean age for this group was 57.9 ± 12.9 years (range 31-84 years). None of the able-bodied matches were previously exposed to the lean-and-release test. None of the able-bodied matches had experienced a fall in the three months prior to participation in this study.

4.2.1.2 Participants with Incomplete SCI

This study included 17 individuals with incomplete SCI (11 females, 6 males). Three participants (PBT02, PBT15 and PBT19) met the study inclusion criteria, but after the testing session it was determined that the lean-and-release test was not suitable for their level of function. These
participants were unable to sufficiently initiate a step to recover balance and fell on every trial; therefore, their data was excluded from the analyses, resulting in a sample of 14 for analyses.

The mean age of all participants with incomplete SCI included in the analysis (n=14) was 58.1 ± 15.8 (range 32-88 years). All participants had a motor incomplete SCI with AIS scores of C or D. Neurological level of injury ranged from C1-L5. The mean time post-injury for these participants was 43.9 ± 42.8 months. Four participants experienced a traumatic SCI (i.e. fall or motor vehicle accident) and ten experienced a non-traumatic SCI (i.e. surgery, arterial/venous malformation, congenital stenosis, blood clot, osteomyelitis, meningioma, or transverse myelitis). Ten participants with incomplete SCI used a gait aid for mobility (i.e. cane or 4-wheeled walker (4WW)) while the other participants did not use a gait aid for daily ambulation (Table 1). The mean preferred gait speed was 0.89 ± 0.28 m/s, ranging from 0.4-1.28 m/s. The mean summative score of lower extremity muscle strength was 88.7 ± 12.5, ranging from 72.5 to 104.5. The mean mini-BESTest score was 16 ± 7.6 (ranging 4 to 25). Five participants (35.7%) experienced at least one fall in the three months prior to the collection. Six participants (42.9%) reported having a fear of falling (Table 1).

The mean age of the participants with incomplete SCI that were excluded from the study was 56.3 ± 7.5 years. Neurological level of injury ranged from T5-L1. The mean time post-injury for these three participants was 177 ± 87.1 months and their causes of injury were non-traumatic (i.e. staph infection, tumour resection, and virus in the spinal cord). These participants of lower function used a 2-wheeled walker (2WW) or 4WW for ambulation. The mean preferred gait speed was 0.27 ± 0.12 m/s; the mean summative motor score of the lower extremity was 74.2 ± 6.9; and the mean mini-BESTest score was 2.3 ± 3.2. One participant (33.3%) experienced at least one fall in the previous three months and one participant (33.3%) reported having a fear of falling (Table 1).
Table 1. Demographics of the participants with incomplete SCI. Abbreviations: LE, lower extremity; mini-BESTest, mini-Balance Evaluation Systems Test; 4WW, 4-wheeled walker; 2WW, 2-wheeled walker. * denotes participants that were excluded from data analyses. ^Neurological level of injury.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Time post-injury (mos.)</th>
<th>Level of injury^</th>
<th>Cause of injury</th>
<th>LE strength (/120)</th>
<th>Preferred gait speed (m/s)</th>
<th>Walking aid</th>
<th>mini-BESTest Score (/28)</th>
<th>Retrospective falls (3 mos.)</th>
<th>Fear of falling</th>
</tr>
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<tbody>
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<td>PBT01</td>
<td>F</td>
<td>61</td>
<td>12</td>
<td>C</td>
<td>Surgery</td>
<td>83.5</td>
<td>0.71</td>
<td>4WW</td>
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<td>1</td>
<td>Y</td>
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<td>M</td>
<td>64</td>
<td>82</td>
<td>T6</td>
<td>Staph infection</td>
<td>80</td>
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<td>4WW</td>
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<td>0</td>
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<td>12</td>
<td>T, L1-2</td>
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<td>32</td>
<td>42</td>
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<td>N</td>
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<td>70</td>
<td>22</td>
<td>T1-6</td>
<td>Osteomyelitis</td>
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<td>1.24</td>
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<td>31</td>
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<td>Level</td>
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<td>Fall Type</td>
<td>Fall Score</td>
<td>Fall Duration</td>
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<td>F</td>
<td>59</td>
<td>13</td>
<td>C1-T1, L2-5</td>
<td>Fall</td>
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<td>0.43</td>
<td>4WW</td>
<td></td>
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<td>M</td>
<td>49</td>
<td>253</td>
<td>T5-6</td>
<td>Tumour</td>
<td>76</td>
<td>0.41</td>
<td>(Canes)</td>
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<td>12</td>
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<td>55</td>
<td>109</td>
<td>C5-6</td>
<td>Fall</td>
<td>94</td>
<td>1.17</td>
<td>Cane</td>
<td>20</td>
<td>1</td>
<td>1</td>
</tr>
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<td>PBT17</td>
<td>F</td>
<td>38</td>
<td>15</td>
<td>T4-5</td>
<td>Arterial venous malformation</td>
<td>74.5</td>
<td>0.94</td>
<td>4WW</td>
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<td>F</td>
<td>54</td>
<td>161</td>
<td>C4</td>
<td>Car accident</td>
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<td>0.81</td>
<td>Cane</td>
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<td>0</td>
</tr>
<tr>
<td>PBT19*</td>
<td>M</td>
<td>56</td>
<td>196</td>
<td>L1</td>
<td>Virus in spinal cord</td>
<td>66.5</td>
<td>0.21</td>
<td>2WW</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PBT20</td>
<td>F</td>
<td>56</td>
<td>14</td>
<td>L5</td>
<td>Surgery</td>
<td>72.5</td>
<td>0.87</td>
<td>None</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PBT22</td>
<td>M</td>
<td>88</td>
<td>64</td>
<td>L3</td>
<td>Blood clot</td>
<td>86</td>
<td>0.77</td>
<td>Cane</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>57.8±14.5</td>
<td>67.4±71.9</td>
<td>86.1±12.9</td>
<td>0.78±0.36</td>
<td>13.6±8.8</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Single Step versus Multi-Step Responses

Reaction timing and movement timing parameters were compared for single step responses and multi-step responses (i.e. first step of the response) for the group with incomplete SCI and able-bodied matches separately. As there were no significant differences between responses for both groups, single and multi-step responses were combined for the analyses of reaction timing and movement timing.

4.4 Behavioural Description of Reactive Stepping

4.4.1 Description of Responses

Able-bodied matches did not experience any falls during the lean-and-release test but showed more multi-step reactions compared to their younger counterparts. Of the 120 trials completed by the able-bodied matches, 55.8 ± 43.4% were single step and 44.2 ± 43.4% were multi-step responses. Four participants (33%) always used the same leg to perform the stepping response.

Of the 130 trials performed by individuals with incomplete SCI, 31.3 ± 40.0% were single step, 61.6 ± 42.3% were multi-step and 7.1 ± 12.5% were falls. Six participants (42.9%) of participants with incomplete SCI performed all stepping responses with the same leg. All participants with incomplete SCI were able to complete 9-10 trials with the exception of two participants who were only able to complete seven (PBT14) and four (PBT04) trials. For 7.5% of the trials performed by individuals with incomplete SCI, participants were unable to reach the 8-12% body weight support threshold due to fear or anxiety. However, a release perturbation was still administered at the maximal body weight support these participants were able to reach and these trials were still included in our analyses. There were no adverse events reported.

4.4.2 Comparison of Responses Between Groups

Individuals with incomplete SCI showed a greater proportion of multi-step responses and falls compared to the able-bodied matches. Results of the Chi-square test showed a significant difference between groups for the single step and non-single step responses, ($\chi^2 = 12.72 \ p<0.01$).
Table 2. Behavioural responses by group. AB, able-bodied; SCI, spinal cord injury.

<table>
<thead>
<tr>
<th></th>
<th>Single step</th>
<th>Multi-step</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB Matches</td>
<td>55.8 ± 43.4%</td>
<td>44.2 ± 43.4%</td>
<td>0%</td>
</tr>
<tr>
<td>SCI</td>
<td>31.3 ± 40.0%</td>
<td>61.6 ± 42.3%</td>
<td>7.1 ± 12.5%</td>
</tr>
</tbody>
</table>

4.5 Electromyography Onset - Reaction Timing

4.5.1 Able-bodied Matches

Similar to the young able-bodied participants, most able-bodied matches showed a consistent pattern of activation over trials (Figure 5). In the able-bodied matches, the only difference compared to the young able-bodied adults was that the supporting VL was activated before the stepping RF (compare Figure 4 with Figure 8a).
**Figure 5.** Muscle activation pattern in a matched able-bodied participant. The average activation pattern of the muscles of the stepping (left plots) and supporting (right plots) legs for an able-bodied match (LR26, female, 56 years old) over ten trials. Time at 0 seconds signifies the point of release, the first vertical line (in red) identifies the average onset of EMG activation, the second vertical line (in blue) identifies the average foot-off timing and the third vertical line (in black) identifies the average foot contact timing over trials.

### 4.5.2 Participants with Incomplete SCI

One participant, PBT04, was excluded from the analysis of EMG onset as the EMG outputs had unidentifiable onset points or excessive noise that disrupted the signal. Over trials, individuals with incomplete SCI showed a more variable pattern of EMG activation following the perturbation (Figures 6 and 7) compared with the able-bodied participants. The average order of EMG onset for the group with incomplete SCI was as follows: stepping MG, supporting SOL, stepping SOL, supporting MG, supporting BF, stepping TA, supporting VL, supporting TA, supporting RF, stepping BF, stepping RF, and stepping VL. Contrary to the able-bodied participants, the stepping TA in individuals with incomplete SCI was activated before the supporting TA, which may suggest that foot-off was attempted earlier during weight shifting onto the supporting leg. The activation of the supporting VL, supporting TA and supporting RF prior to the stepping BF, stepping RF and stepping VL suggest compensatory weight shifting to allow for foot-off (Figure 8).
Figure 6. Muscle activation pattern in a participant with incomplete SCI. The average activation pattern of the muscles of the stepping (left plots) and supporting (right plots) legs for one participant with incomplete SCI (PBT06) over ten trials. Time at 0 seconds signifies the point of release, the first vertical line (in red) identifies the average onset of EMG activation, the second vertical line (in blue) identifies the average foot-off timing and the third vertical line (in black) identifies the average foot contact timing over trials. Some muscles do not have an identifiable onset of EMG activation, as shown above.
Figure 7. Muscle activation pattern in a participant with incomplete SCI. The average activation pattern of the muscles of the stepping (left plots) and supporting (right plots) legs for one participant with incomplete SCI (PBT13) over ten trials. Time at 0 seconds signifies the point of release, the first vertical line (in red) identifies the average onset of EMG activation, the second vertical line (in blue) identifies the average foot-off timing and the third vertical line (in black) identifies the average foot contact timing over trials.

A. Able-bodied Matches
Figure 8. Muscle activation timing by group. A. Able-bodied matches; B. Participants with SCI. The muscles are plotted in order of activation; the first six muscles are of the stepping leg and the latter six are of the supporting leg. Error bars reflect the standard deviation of each mean value.

4.5.3 Coefficient of Variation

The CVs for the mean EMG onset for all muscles and participants in the able-bodied matches and incomplete SCI groups were calculated. There were no significant differences between groups for all muscles of the lower extremity (Table 3).

Table 3. Coefficient of variation of muscle activation timing for each muscle, by group. AB, able-bodied; SCI, spinal cord injury; TA, tibialis anterior; SOL, soleus; MG, medial gastrocnemius; RF, rectus femoris; VL, vastus lateralis; BF, biceps femoris.

<table>
<thead>
<tr>
<th>Muscle</th>
<th>AB Matches</th>
<th>SCI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supporting TA</td>
<td>0.28 ± 0.16</td>
<td>0.34 ± 0.27</td>
<td>0.557</td>
</tr>
<tr>
<td>Supporting SOL</td>
<td>0.26 ± 0.16</td>
<td>0.32 ± 0.17</td>
<td>0.374</td>
</tr>
<tr>
<td>Supporting MG</td>
<td>0.31 ± 027</td>
<td>0.31 ± 0.16</td>
<td>0.970</td>
</tr>
<tr>
<td>Supporting RF</td>
<td>0.25 ± 0.15</td>
<td>0.34 ± 0.20</td>
<td>0.316</td>
</tr>
<tr>
<td>Supporting VL</td>
<td>0.32 ± 0.19</td>
<td>0.40 ± 0.22</td>
<td>0.364</td>
</tr>
</tbody>
</table>
4.5.4 Comparison of EMG Onset Across Groups

Significant differences between groups were found for the EMG onset of the supporting TA (p=0.005) and stepping TA (p=0.021) (Table 4). The EMG onset of the ten remaining muscles were not significantly different between able-bodied matches and participants with incomplete SCI.

Table 4. Timing of muscle activation by group. Significance (p<0.05) is marked with an asterisk, representing a significant difference between groups of the onset of EMG for those specific muscles. ^ denotes the muscles that required the non-parametric Mann-Whitney U test to compare means. AB, able-bodied; SCI, spinal cord injury; TA, tibialis anterior; SOL, soleus; MG, medial gastrocnemius; RF, rectus femoris; VL, vastus lateralis; BF, biceps femoris.

<table>
<thead>
<tr>
<th></th>
<th>AB Matches</th>
<th>SCI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supporting TA^</td>
<td>86 ± 23 ms</td>
<td>143 ± 80 ms</td>
<td>0.005*</td>
</tr>
<tr>
<td>Supporting SOL^</td>
<td>65 ± 15 ms</td>
<td>76 ± 21 ms</td>
<td>0.067</td>
</tr>
<tr>
<td>Supporting MG</td>
<td>70 ± 17 ms</td>
<td>78 ± 25 ms</td>
<td>0.406</td>
</tr>
<tr>
<td>Supporting RF</td>
<td>113 ± 28 ms</td>
<td>144 ± 63 ms</td>
<td>0.150</td>
</tr>
<tr>
<td>Supporting VL</td>
<td>122 ± 56 ms</td>
<td>141 ± 81 ms</td>
<td>0.271</td>
</tr>
<tr>
<td>Step</td>
<td>BF 102 ± 30 ms</td>
<td>90 ± 17 ms</td>
<td>0.262</td>
</tr>
<tr>
<td>------</td>
<td>----------------</td>
<td>-------------</td>
<td>--------</td>
</tr>
<tr>
<td>Stepping TA</td>
<td>90 ± 20 ms</td>
<td>140 ± 69 ms</td>
<td>0.021*</td>
</tr>
<tr>
<td>Stepping SOL</td>
<td>65 ± 16 ms</td>
<td>78 ± 26 ms</td>
<td>0.213</td>
</tr>
<tr>
<td>Stepping MG</td>
<td>70 ± 11 ms</td>
<td>76 ± 19 ms</td>
<td>0.425</td>
</tr>
<tr>
<td>Stepping RF</td>
<td>134 ± 93 ms</td>
<td>168 ± 59 ms</td>
<td>0.223</td>
</tr>
<tr>
<td>Stepping VL</td>
<td>164 ± 83 ms</td>
<td>227 ± 130 ms</td>
<td>0.212</td>
</tr>
<tr>
<td>Stepping BF</td>
<td>88 ± 16 ms</td>
<td>149 ± 150 ms</td>
<td>0.514</td>
</tr>
</tbody>
</table>

4.6 Movement Timing

Foot-off timing, foot contact timing and swing duration of the stepping leg for able-bodied matches and participants with incomplete SCI were reported (Table 5). There were no significant differences between groups for foot-off timing (p=0.599), foot contact timing (p=0.076) or swing duration (p=0.272).

Table 5. Foot-off timing, foot contact timing and swing duration by group. AB, able-bodied; SCI, spinal cord injury.

<table>
<thead>
<tr>
<th></th>
<th>AB Matches</th>
<th>SCI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot-off (ms)</td>
<td>366 ± 95</td>
<td>384 ± 69</td>
<td>0.599</td>
</tr>
<tr>
<td>Foot contact (ms)</td>
<td>518 ± 133</td>
<td>569 ± 88</td>
<td>0.076</td>
</tr>
<tr>
<td>Swing (ms)</td>
<td>151 ± 45</td>
<td>185 ± 49</td>
<td>0.272</td>
</tr>
</tbody>
</table>

4.7 Correlations between Proportion of Single steps and Scores on Clinical Measures

There were no significant correlations between percentage of single step responses with: fear of falling (ρ = 0.022); fall history (ρ = 0.131); lower extremity strength (r = 0.441); mini-BEST total scores (r = 0.262); mini-BEST reactive component scores (r = 0.472); gait speed (r=0.020) or step length (r=0.118) (Figure 8).
A. % Single step and LE strength

B. % Single step and mini-BESTest score

C. % Single step and reactive mini-BESTest score
Figure 9. Percentage of single step responses compared to clinical measures. A. Lower extremity strength; B. mini-BESTest; C. Reactive mini-BESTest score; D. Gait speed; E. Step length. Each dot represents data from one participant with SCI. LE, lower extremity; mini-BESTest, mini-Balance Evaluation Systems Test.
5 Discussion

5.1 Summary of Findings

According to our results, reactive stepping ability is likely reduced in individuals with incomplete SCI compared to able-bodied adults as evidenced by the higher occurrence of multi-steps and falls. As hypothesized, individuals with incomplete SCI took more steps to regain their balance following an external perturbation. Contrary to our hypothesis, individuals with incomplete SCI did not have slower reaction and movement times; the timing of muscle activation was not significantly different between individuals with incomplete SCI and able-bodied participants for ten of twelve lower extremity muscles. However, our hypothesis was supported by the timing of activation of the supporting and stepping TA as the individuals with incomplete SCI demonstrated significantly slower activation compared to the able-bodied matches. Between participants with incomplete SCI and able-bodied matches, the timing of foot-off and foot contact and swing duration of the stepping leg were not significantly different. There were no significant correlations between the percentage of single step responses and a fear of falling, recent history of falls, lower extremity strength, mini-BESTest scores, gait speed or step length. The lean-and-release test is likely most appropriate for individuals with incomplete SCI who are capable of ambulating more than one step without assistance or a gait aid as the three participants whose data were excluded were unable to step independently. In summary, the findings identified deficits in reactive balance control in individuals with incomplete SCI, which may be used to guide reactive balance training and assessment in SCI rehabilitation practice.

5.2 Timing versus Magnitude of Stepping Response

Participants with incomplete SCI took a greater proportion of multi-steps and falls when completing the lean-and-release test compared to the able-bodied participants. However, this finding was not explained by a delay in the initiation of the first reactive step, as there were no differences between groups for the movement timing data. Similarly, onset of EMG activation in the lower extremity muscles was not significantly different between participants with incomplete SCI and able-bodied matches, with the exception of the stepping and supporting TA. The
participants with SCI showed slower activation of these muscles on average, which may have contributed to the group differences in the behavioural response. It is possible that participants with SCI took shorter steps than their able-bodied counterparts, necessitating multiple steps in order to replace the extrapolated COM within the BOS. Indeed, this difference in step length was observed in a subset of our participants: seven participants with SCI and seven age- and sex-match able-bodied participants (Yoo et al., 2018). The individuals with SCI stepped 38.3 ± 10.7 cm in the first reactive step, as measured by the trajectory of their centre of pressure, whereas the able-bodied matches stepped 41.4 ± 12.7 cm (Yoo et al., 2018). Similarly, Arora (2018) recently reported that ambulatory individuals with incomplete SCI demonstrated a reduced ability to increase their lateral margin of stability (i.e. the distance between their extrapolated COM and the lateral border of their BOS) when taking a compensatory step in response to a slip perturbation while walking. It is possible that the impaired behavioural responses observed in the participants with SCI resulted from a reduced magnitude of the response as opposed to an impaired timing of the response.

5.3 Comparison of Stepping Response Across Patient Populations

Reactive stepping ability of individuals with incomplete SCI has similarities to that of older adults and individuals who have experienced a stroke. The participants with incomplete SCI showed more multi-steps and falls compared with the young able-bodied participants during the lean-and-release test. Previous studies have similarly reported that compared to their younger counterparts, older adults have a higher tendency to take multiple steps (Luchies et al., 1994; McIlroy & Maki, 1996; Wolfson et al., 1986) or fail to recover their balance completely (Pavol, Runtz, Edwards, & Pai, 2002). Likewise, some individuals with stroke show ineffective step responses, i.e. steps with inadequate foot clearance or complete absence of a step attempt, resulting in a fall (Lakhani et al., 2011; Mansfield et al., 2011, 2012).

Compared to younger adults, older adults have a reduced step length and step speed during reactive stepping (Hageman & Blanke, 1986; Hsiao-Wecksler & Robinovitch, 2007; Medell & Alexander, 2000; Oberg, Karsznia, & Oberg, 1993). Individuals with incomplete SCI also showed reduced step length during the lean-and-release test compared to able-bodied individuals (Yoo et al., 2018). In contrast to the previous findings concerning step speed, there were no
differences between individuals with incomplete SCI and the able-bodied participants. Contrary to the individuals with incomplete SCI studied here, individuals with stroke have slower foot-off timing compared to able-bodied individuals (Lakhani et al., 2011; Mansfield et al., 2013).

EMG has not been previously studied in the older adult and stroke populations with the lean-and-release test; however, there were significant differences between individuals with incomplete SCI and able-bodied matches for two muscles of the lower extremity with respect to EMG onset data. The significant delay of onset of EMG for the stepping and supporting TA in individuals with incomplete SCI likely reflects reduced limb control as a result of sensorimotor impairments. In addition, the onset of EMG was more variable amongst individuals with incomplete SCI.

5.4 Clinical Use

The lean-and-release test is a promising measure of reactive balance control that has been implemented within stroke rehabilitation (Inness et al., 2015). The findings of this thesis suggest that the behavioural component of the lean-and-release test may prove useful for SCI clinical practice as this outcome has the potential to discriminate between individuals with SCI and able-bodied people (i.e. significant between-group differences were found for behavioural response). Our findings suggest, however, that the test is appropriate only for a subset of individuals with incomplete SCI – those who are able to take more than one step independently (i.e. without a gait aid or physical assistance). The EMG onset and movement timing data did not distinguish between the SCI and able-bodied groups; hence, EMG and force plate equipment are likely not needed in the clinical setting to measure reactive balance. Further, these pieces of equipment are rarely found in clinical settings; thus, the clinical utility of the lean-and-release test may be increased by focusing solely on the behavioural outcomes. The behavioural component of the lean-and-release test does not require equipment or training and does not require much time to complete. The angle of the lean could be controlled by marking foot placements relative to the release mechanism and cable as a form of standardization.

There were no significant correlations between the behavioural response and clinical measures, including a history of falls for individuals with incomplete SCI, which does not support convergent validity of the lean-and-release test. However, the sample size used for the correlation analyses was small (i.e. n=14) so the analyses may have been underpowered. Convergent validity, a sub-type of construct validity, addresses the correlation between two
measures testing the same construct (Streiner, Norman, & Cairney, 2008). Interestingly, some participants with moderately high strength and balance scores showed no single step responses (Figure 7). These participants may have chosen to take multi-steps, which identifies a potential issue with our testing instructions. In the future, participants could be instructed to take a single step and to only take additional steps if necessary for balance recovery.

5.5 Demographics of Participants with SCI

Our sample included a greater proportion of individuals with non-traumatic SCI and a greater proportion of females, which are not reflected in the larger SCI population. In the past, the prevalence of traumatic SCI was reported as greater than non-traumatic SCI (Couris et al., 2010), but this trend is shifting. However, there is a paucity of high quality epidemiological data for non-traumatic SCI due to conditions that are heterogeneous and difficult to distinguish (New et al., 2017). Non-traumatic SCI is estimated to occur two to three times more than traumatic SCI (Nesathurai, 2009). A recent study found that the estimated prevalence of non-traumatic SCI to be 367 cases per million people (New, Farry, Baxter, & Noonan, 2013). One possible reason why our study included a large proportion of participants with non-traumatic SCI may have been due to our small sample with participants being enrolled on a first-come first-serve basis. In order to recruit a sample more representative of the Canadian SCI population in the future, we could use a purposeful sampling method.

Although there is a higher proportion of males that experience SCI (Couris et al., 2010), the higher enrollment of females in this study may be explained by a greater concern about falling in females. Several studies of older adults and individuals with stroke found that females were more likely to have a fear of falling compared to their male counterparts (Andersson, Kamwendo, & Appelros, 2008; Gillespie & Friedman, 2007; Lebouthillier, Thibodeau, & Asmundson, 2013; Pohl, Ahlgren, Nordin, & Lundquist, 2015). Moreover, this study was linked to a randomized controlled trial comparing two balance interventions; participation in a balance training program may have been more appealing to females than males.

5.6 Limitations

There are several limitations of this research worth noting. First, as mentioned above, the demographics of our sample of individuals with incomplete SCI (i.e. primarily female and SCI of
non-traumatic origin) is not representative of the Canadian SCI population. Further, the participants with SCI studied here had a high level of function as they could all take several steps independently (i.e. without a gait aid or physical assistance from another person). Hence, a small subset of the SCI population was studied and this limits the generalizability of the findings. Second, it was challenging to truly measure reactive balance as participants were made aware that there would be a perturbation during the lean-and-release test. We attempted to reduce anticipatory balance strategies by interspersing false trials (i.e. release mechanism was not triggered) among the release trials and randomizing all trials. In addition, the perturbation was given at various points during the 30-second collection period for each trial. Third, participants were not instructed to take only a single step if possible. Participants may have voluntarily taken more than one reactive step, which would have affected the significance of the behavioural response results. Fourth, some EMG data were unusable due to excessive noise or an unclear signal of muscle activation. These issues may have been caused by cable artifact, poor contact of the EMG lead to the skin, or excess adipose tissue of the participants. We tried to prevent signal loss by cleaning the skin with alcohol swabs and using tape to reinforce EMG leads to the participants’ skin. We recorded the activity of the rectus femoris, but we were unable to accurately capture the activity of the deeper hip flexors, the iliopsoas, with surface EMG. Lastly, the correlation analyses were likely underpowered; the relationship between percentage of single steps and clinical measures requires further investigation with a larger sample size.

5.7 Potential implications

Through this study, we described the reactive stepping ability of individuals with incomplete SCI and compared this ability with that of able-bodied individuals. We are among the first to demonstrate that individuals with SCI have impaired reactive stepping responses. The findings may suggest that the lean-and-release test is a safe and clinically feasible method of measuring and evaluating reactive balance control in individuals with incomplete SCI. The findings may also provide information pertaining to what needs to be targeted in balance rehabilitation, namely training participants to take longer steps rather than reacting more quickly. Most importantly, our findings may influence how physical therapists measure and address reactive balance deficits for the SCI population. If reactive balance control can be improved in individuals with incomplete SCI, this may lead to a reduction in falls and fear of falling.
6 Conclusion

Reactive stepping ability of our participants with incomplete SCI was reduced compared to able-bodied individuals as shown by the higher occurrence of multi-steps and falls. However, the timing of muscle activation was not significantly different between individuals with incomplete SCI and able-bodied individuals for ten of the 12 lower extremity muscles investigated. Foot-off and foot contact timing were also not significantly different between groups. There were no significant correlations between behavioural response and clinical measures of strength and balance, fall history and a fear of falling. Our findings suggest that reactive balance control should be addressed in the rehabilitation of individuals with incomplete SCI. Our findings may guide how reactive balance ability is assessed and training in individuals with incomplete SCI.

The lean-and-release test is not suitable for all individuals with incomplete SCI; we determined that the test is most suitable for individuals who are able to take more than one step independently (i.e. without physical assistance or a gait aid). In regards to clinical utility, the behavioural component of the lean-and-release test is sufficient to evaluate reactive balance as EMG and force plate data did not identify balance deficits in this study.
Chapter 7
Future Directions

7 Future Directions

Future work could provide additional description of the reactive stepping ability of individuals with incomplete SCI. Motion capture analysis could be used to quantify step length, body segment movement patterns, and the use of hip or ankle strategies during the lean. It is not accurate to record centre of pressure trajectories using the force plates as not all participants were able to fully step onto the force plates during their reactive response. For the cases and individuals where the reactive steps were partially or completely off the force plates, the motion capture data would be useful in describing the reactive movement patterns. Motion capture could also be used to investigate any impairments in toe clearance for both the initial step and any subsequent steps taken in the case of a multi-step response. Insufficient toe clearance poses as a tripping hazard and increases one’s risk of falling. Additionally, the magnitude of muscle activation following the release could be analyzed.

Anticipatory balance is another component of balance that warrants further analysis in the SCI population. In this study participants were made aware that the release mechanism may be triggered during each trial, so there were likely some anticipatory strategies involved; however, it is unknown if and how these anticipatory strategies in individuals with incomplete SCI differ from able-bodied individuals.

Older adults initiated stepping at lower levels of instability (Jensen et al., 2001; Mille et al., 2003). Varying levels of instability were not systematically tested for this thesis, but could be in the future. Instead we asked all participants to achieve 8-12% of body weight support when leaning. This may partially explain our observation that some able-bodied participants attempted to use a hip strategy to maintain balance rather than taking a reactive step. The lean angle and perturbation intensity could also be investigated to determine if these test parameters can better identify the deficits of reactive stepping ability in individuals with incomplete SCI.

Future research should also focus on the study of reactive balance control during walking since most falls in SCI occur during this activity (Brotherton et al., 2007). To our knowledge, only
Arora and colleagues (2018) have studied reactive responses during a loss of balance while walking.

Further analysis of the psychometric properties of the lean-and-release test is required prior to clinical use. This type of analysis would require a larger sample size and data set. The sensitivity of the lean-and-release test will reflect its clinical and rehabilitative usefulness. Although this study was conducted in a controlled lab environment, the lean-and-release would need to be conducted in a different environment for clinical usability and feasibility.

Lastly, investigation of reactive balance training in SCI is warranted as it has shown to be effective in the stroke population (Mansfield et al., 2015). Unger and colleagues (2018) are currently completing a single-site, randomized clinical trial comparing clinical outcomes following eight weeks of perturbation-based balance training or eight weeks of conventional balance training for individuals with chronic incomplete SCI. The findings from this study may provide further evidence for the inclusion of the assessment and training of reactive balance in SCI rehabilitation.
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