A STEP TOWARDS UNDERSTANDING BALANCE CONTROL IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

A Thesis Submitted to
the College of Graduate and Postdoctoral Studies
In Partial Fulfillment of the Requirements for
The Degree of Doctor of Philosophy in
The Department of Health Sciences, College of Medicine
University of Saskatchewan, Saskatoon

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ABSTRACT

Purpose: Frequent falls are reported by individuals with spinal cord injury (SCI) suggesting impairments in their balance control. This thesis examined balance assessment and balance control in individuals with SCI.

Methods and Results: To investigate the effects of light touch on standing balance, center of pressure (COP) sway during standing was measured in 16 participants with incomplete SCI (iSCI) and 13 able-bodied (AB) participants. Participants with iSCI showed reduction in COP sway with light touch similar to AB participants.

To study the association between stability during normal walking (NW) and unexpected slip intensity, NW behaviour and intensity of an unexpected slip perturbation were assessed in 20 participants with iSCI, and 16 AB participants. Participants with iSCI demonstrated greater stability by walking slower, taking shorter steps, and more time in double support. Walking slower was associated with lower slip intensity in individuals with iSCI.

To study reactive balance control, change in margin of stability with a compensatory step, activation of lower extremity muscles, and change in limb velocity trajectories in response to an unexpected slip perturbation were studied in 16 participants with iSCI and 13 AB participants. Participants with iSCI demonstrated limitations in reactive responses including a smaller increase in lateral margin of stability, slower onset of trail limb tibialis anterior activity, and decreased magnitude of trail limb soleus activity.

To identify balance measures specific to individuals with SCI, a systematic review of 127 articles was conducted. Thirty balance measures were identified; 11 evaluated a biomechanical construct and 19 were balance scales designed for use in clinical settings. All balance scales had high clinical utility. The Berg Balance Scale and Functional Reach Test were valid and reliable, while the Mini Balance Evaluation Systems Test was most comprehensive.

Conclusions: Individuals with iSCI have impaired balance control, as evidenced by limitations in reactive balance; however, they have the ability to modify their balance, as demonstrated by greater stability during NW and with light touch while standing. No single balance measure met all criteria of a useful measure - high clinical utility, strong psychometric properties, and comprehensiveness in the SCI population. Combined, the findings highlight the need for the comprehensive assessment and rehabilitation of balance control after iSCI.

PREFACE AND AUTHOR CONTRIBUTIONS

I, Tarun Arora, was the primary author of all chapters within this thesis. Chapters two and five represent manuscripts that have either been submitted or have been published in peer-reviewed journals. Chapter three and four will be submitted for publication in a peer-reviewed journals. Author contributions have been discussed and approved by the student advisory committee.

Chapter two represents a manuscript that has been published in the Neuroscience Letters journal. The manuscripts was co-authored by Drs. Kristin E Musselman, Joel Lanovaz, and Alison Oates. I designed the research question, collected and analyzed data, and prepared the manuscript under the supervision of Drs. Oates and Musselman. Dr. Lanovaz contributed to data collection, analysis and interpretation, and in reviewing the manuscript.

Chapter three and four represent two manuscripts that were co-authored by Drs. Kristin E Musselman, Joel Lanovaz, Gary Linassi, Cathy Arnold, Stephan Milosavljevic, and Alison Oates. I contributed to components of research design, and was responsible for data collection, processing, and writing of the manuscripts under the supervision of Drs. Oates and Musselman. All co-authors were involved in research design and review of the manuscript. Dr. Lanovaz contributed to data collection, analysis and interpretation. Dr. Linassi assisted in participant recruitment. The manuscripts forming chapter three and four will be submitted for publication in peer-reviewed journals.

Chapter five represents a manuscript that has been prepared and submitted to the Journal of Spinal Cord Medicine and was co-authored by Dr. Alison Oates, Kaylea Lynd, and Dr. Kristin E Musselman. The manuscript is currently being revised for consideration for publication in the Journal of Spinal Cord Medicine. I designed the research question, devised the key search terms, conducted the database searches, and prepared the manuscript under the supervision of Drs. Musselman and Oates. I also carried out data extraction and synthesis along with the co-authors.

ACKNOWLEDGEMENTS

गुरुर्ब्रह्मा गुरुर्विष्णुर्गुरुर्देवो महेश्वरः ।
गुरुरेव परं ब्रह्म तस्मै श्रीगुरवे नमः ॥

I am indebted to my supervisors Drs. Alison Oates and Kristin Musselman for their immense support in the form of valuable guidance and encouragement throughout my Ph.D. This Ph.D. would not have been possible without their guidance. I am also thankful to Dr. Joel Lanovaz for sharing his expertise for biomechanics, which helped me tremendously with the Biomechanical data analysis. I am thankful to my research advisory committee members Drs. Gary Linassi and Steve Milosavljevic for their valuable feedback on my work. I am also thankful to Dr. Cathy Arnold for chairing the committee meetings and being a positive support.

मातृपितृकृताभ्यासो गुणितामेति बालकः ।
न गर्भच्युतिमात्रेण पुत्रो भवति पण्डितः ।।

No child is born learned, it is the parents' efforts that help him/her to acquire knowledge – sometime by their direct teachings and other times through their sacrifices. Attaining this Ph.D. degree would not have been possible without the sacrifices of my mom and dad who selflessly supported me to come to Canada to pursue my academic goals.

I thank all the research participants who volunteered to participate in the study. In addition to the data I collected, I learnt something new from their experiences and stories.

I am thankful for the support from the Department of Health Sciences at the College of Medicine, School of Physical Therapy, and College of Kinesiology for their administrative assistance.

I am thankful for the financial support in form of research funds from the 2015-2018 Ph.D. University Graduate Scholarship, the 2014-17 Spinal Cord Injury - Saskatchewan Health Research Foundation grant, and 2014-15 Health Science Research Support Award.

I am also thankful to friends I made during my Ph.D. This journey was more enjoyable with them around.

I am grateful for the fulfilling experience I had during my PhD program.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

CONCEPTUAL DEFINITIONS

Fall: an event which results in a person coming to rest inadvertently on the ground or floor or other lower level (World Health Organization, 2007)

Center of mass: an average position of all the parts of the body weighted according to their masses (Winter, 1995)

Base of support: area of support formed beneath an object or person that includes all points of contact (Winter, 1995)

Center of pressure: the point of application of vertical ground reaction force (Winter, 1995)

Balance: instantaneous state of the body when the vertical projection of the center of mass falls within the base of support (Pollock, Durward, Rowe, & Paul, 2000)

Balance control or postural control: inherent ability of an individual to maintain, achieve or restore a state of balance during any posture or activity (Pollock et al., 2000)

Stability: property of a body by virtue of which it moves from a state of unbalance to a balanced state; or it resists becoming unbalanced from a balance state (Loubert, 2011)

LIST OF COMMON ABBREVIATIONS USED

AB	Able-bodied
ABC Scale	Activity Specific Balance Confidence Scale
ABLE	Activity Based Level Evaluation
AIS	American Spinal Injury Association Impairment
BBS	Berg Balance Scale
BOS	Base of Support
COM	Center of Mass
COP	Center of Pressure
CPG	Central Pattern Generator
EMG	Electromyography
FRT	Functional Reach Test
GM	Gluteus Medius
iSCI	Incomplete Spinal Cord Injury
ISNSCI	International Standards of Neurological Classification of Spinal Cord Injury
MiniBESTest	Mini Balance Evaluation Systems Test
NW	Unperturbed Normal Walking
SCI	Spinal Cord Injury
SCIFAP	Spinal Cord Injury Functional Ambulation Profile
SOL	Soleus
TA	Tibialis Anterior
TUG	Time Up and Go
XCOM	Extrapolated Center of mass

LIST OF APPENDICES

CHAPTER ONE: INTRODUCTION

Injury to the spinal cord can be catastrophic for any individual, their family, and the community. Motor, sensory, and autonomic dysfunctions can lead to various health complications such as sarcopenia, spasticity, osteoporosis, bowel and bladder dysfunction, cardiovascular problems, pressure ulcers, depression, and a perception of accelerated ageing (Elliott & Frank, 1996; Noreau, Proulx, Gagnon, Drolet, & Laramee, 2000; Phillips et al., 1998) These health complications can affect overall quality of life of these individuals. Individuals with SCI are re-hospitalized 2.6 times more often compared to the general population (Dryden et al., 2004). The impact is not limited to the individual with the SCI: The caregivers also experience physical and emotional stress (Weitzenkamp, Gerhart, Charlifue, Whiteneck, & Savic, 1997). In Canada, the annual economic burden from SCI is estimated to be $2.67 billion (Krueger, Noonan, Trenaman, Joshi, & Rivers, 2013), which results from direct (such as health care, equipment, long-term care, etc.) and indirect (losses from reduction in productivity) costs associated with SCI.

Promoting ambulation among individuals with SCI can be an effective way to improve health such as improving muscles mass, preventing loss of bone mass, and functional independence among individuals with SCI (Behrman et al., 2005; Fritz et al., 2011; Giangregorio et al., 2006; Giangregorio & Blimkie, 2002; Harkema, Schmidt-Read, Lorenz, Edgerton, & Behrman, 2012). The ability to walk is also among the top-most priorities of individuals with SCI (Simpson, Eng, Hsieh, & Wolfe, 2012), and a majority of individuals with an incomplete SCI regain the ability to walk (Dobkin et al., 2006). The challenge is to walk safely without falling as 75% of individuals with incomplete SCI (iSCI) report at least one fall in a year and 48% report recurrent falls (Brotherton, Krause, & Nietert, 2007; Jorgensen et al., 2017). A strong emphasis is placed on treadmill training to generate rhythmic and reciprocal stepping of the legs; however, walking involves maintaining balance control in addition to stepping (Zehr, 2005). Rhythmic stepping is considered to be controlled by a network of specialized inter-neurons called a central pattern generator (CPG), which requires input from supraspinal centres such as the motor cortex, cerebellum and brain stem, and sensory feedback from the peripheral sensory organs for locomotion (Barthélemy, Grey, Nielsen, & Bouyer, 2011; Zehr, 2005). Injury to the spinal cord can impair the communication between CPGs, supraspinal centres and peripheral feedback, thus impairing walking.

The objectives of this thesis are to review how balance is assessed in individuals with SCI and to develop a better understanding of balance control in individuals with motor iSCI. Chapter one reviews the etiology and classification of SCI, the demographics of those living with SCI in Canada, and problem of falls in this population. The first chapter also reviews balance control in those with and without SCI. Chapter two investigates the effect of light fingertip touch on the standing balance of individuals with chronic iSCI, and the relationships between the effect of light touch and the clinical scores of proprioception and cutaneous pressure sensation in the extremities. Chapter three investigates walking stability during unperturbed normal walking (NW) in individuals with chronic iSCI and studies the association between walking stability and slip intensity of an unexpected slip perturbation. Chapter four investigates the reactive responses to an unexpected slip perturbation in individuals with chronic iSCI by studying the reactive change in margin of stability, and onset and magnitude of electromyography activity. Chapter five reviews the current state of balance assessment in the SCI population and provides recommendations for balance assessment in clinical settings on the basis of clinical utility, psychometric properties, and comprehensiveness of the measures in the SCI population. Chapter six discusses the contributions of chapters two to five to the overarching theme of this thesis and identifies their strengths and limitations. Chapter six also gives directions for the future research in the area of balance control after iSCI.

1.1 Spinal Cord Injury

1.1.1 Severity and classification.

The spinal cord consists of ascending and descending tracts, inputs from different sensory modalities, and autonomous circuits capable of producing motor outputs (Rossignol & Frigon, 2011). The spinal cord extends from the brainstem to the first lumbar vertebra and consists of 31 segments – eight cervical, 12 thoracic, five lumbar, five sacral, and one coccygeal, which extend to the peripheral body as nerve roots (Kirshblum et al., 2011). The most distal part of the spinal cord is the conus medullaris and the cauda equina is a bundle of lumbosacral nerve roots that originate in the region of the conus medullaris. Internally, the matter within the spinal cord is arranged such that the cell bodies of motor and sensory neurons form the central H-shaped gray region, whereas the white matter peripheral to the gray matter is formed of the myelinated axons of the nerve cells. Injury to the spinal cord disrupts the conduction of information across the lesion leading to impairments in motor, sensory and autonomic functions. The extent and

severity of impairments depends on the neurological level and completeness of injury, respectively. On the basis of neurological level, an injury can be broadly categorized as tetraplegia or paraplegia. Tetraplegia refers to injury or damage to the cervical segments of the spinal cord, whereas paraplegia refers to injury or damage to the thoracic, lumbar, or sacral segments of the spinal cord (Kirshblum et al., 2011). Impairments are observed below the level of lesion, typically involving all four extremities and the trunk in individuals with tetraplegia, whereas there is sparing of upper extremity function in individuals with paraplegia. Paraplegia also includes injury to the cauda equina or conus medullaris, but not injuries to the lumbosacral plexus or injuries to the peripheral nerves outside the neural canal.

The severity of injury depends on the completeness of the injury, which can be rated using the American Spinal Injury Association Impairment Scale (AIS). Each SCI is given a rating of grade A, B, C, D or E as per the International Standards of Neurological Classification of Spinal Cord Injury (ISNSCI) (Kirshblum et al., 2011). Grade A indicates a complete injury, with no motor or sensory function preserved below the neurological level of injury, including the sacral segments S4-S5. Grade B is an incomplete, or motor complete, injury as there is sensory sparing, but no motor function below the neurological level of injury, including the sacral segments. Grades C and D indicate motor incomplete injuries. In Grade C, more than half of the key muscles below the neurological level of lesion do not have a minimum strength to move the body segments against gravity; whereas in Grade D, at least half of these key muscles have such strength. Grade E indicates normal motor and sensory function in all the segments in someone who had prior deficits. Depending on the location of lesion within the spinal cord, different syndromes with characteristic clinical presentations can be observed after an iSCI – central cord, Brown-Sequard, anterior cord, posterior cord syndrome, cauda equina, and conus medullaris syndrome (Kirshblum et al., 2011; McKinley, Santos, Meade, & Brooke, 2007). Central cord is the most common of all clinical syndromes and involves greater weakness in the upper extremities than the lower extremities, and motor function is more impaired than sensory function (Nowak, Lee, Gelb, Poelstra, & Ludwig, 2009). Brown-Sequard syndrome results from a hemisection of the spinal cord such as from a knife wound. This syndrome leads to ipsilateral loss of proprioception, vibration sense, and motor control, whereas there is a contralateral loss of pain and temperature sensation below the level of lesion (Kirshblum et al., 2011). Anterior cord syndrome involves mainly the loss of motor function, and pain and temperature sensation below

the level of lesion (Schneider, 1955). Posterior cord syndrome is the rarest of all syndromes and leads to a loss of proprioception and vibration sense, but sparing of pain and temperature sensation, and motor control (McKinley et al., 2007). Cauda equine syndrome results from injury to the lumbosacral nerve roots outside the spinal canal leading to lower motor neuron symptoms such as flaccid paralysis, loss of reflexes, and loss of sensation (Gitelman et al., 2008). Conus medullaris is an injury to the sacral cord and lumbar nerve roots within the spinal canal, and is characterized by both upper and lower motor neuron signs (McKinley et al., 2007).

1.1.2 Epidemiology.

In Canada, over 86,000 people are living with a spinal cord injury (SCI) and every year 4,300 new occurrences of SCI are reported (Farry & Baxter, 2010). The etiology of SCI varies between regions and countries: In Canada, about 42% of new injuries result from a traumatic event (e.g. motor vehicle accident, falls, etc.), and 58% from non-traumatic causes (e.g. degenerative changes, infections, malignancy, etc.). Traumatic injuries are most common in adolescent and younger adults due to motor vehicle and sporting accidents, and violence, whereas non-traumatic injuries are more common in older individuals over 70 years (Dryden et al., 2003; Pickett, Campos-Benitez, Keller, & Duggal, 2006). Males are about three times more likely to sustain a SCI compared to females - the sex difference being greater for traumatic injuries than non-traumatic causes of SCI (Couris et al., 2009; Dryden et al., 2003). About 43% of individuals with SCI are living with a tetraplegia; the other 56% are living with paraplegia (Farry & Baxter, 2010). About 35% of the traumatic lesions lead to a complete injury (AIS A) (Pickett et al., 2006). Among iSCI, AIS D is most common outcome, followed by AIS C and AIS B, respectively, and central cord syndrome is the most common clinical presentation, reported in 35% of new injuries (Pickett et al., 2006).

In Canada, the annual economic burden from SCI includes $1.57 billion in direct costs associated with injury-related expenditure by the patient and/or the caregivers such as initial and subsequent hospitalization, health care practitioners, medication, equipment, home modifications, etc. (Krueger et al., 2013). Indirect costs constitute $1.10 billion, and result from the losses that occur due to decreased productivity due to associated morbidity and mortality. These costs depend on the severity of injury, ranging from $1.5 million (for someone with an

incomplete paraplegia) to $3 million (for someone with a complete tetraplegia) (Krueger et al., 2013).

1.2 Falls Among Individuals With SCI: A Pressing Concern

Depending on the neurological level and completeness of injury, varying levels of motor and sensory impairments are experienced. The motor and sensory impairments from a SCI limit feedback about the body's orientation from sensory organs, and also reduce the ability to generate quick and strong movements, which has the potential to predispose these individuals to falls.

Seventy five percent of ambulatory individuals with iSCI experience at least one fall per year (Brotherton et al., 2007); whereas 48% report recurrent falls (Jorgensen et al., 2017). The incidence of falls in individuals with iSCI is similar to individuals with stroke (73%) (Forster & Young, 1995), and higher than that reported in Canadian seniors (33%))(Do, Chang, Kuran, & Thompson, 2015), or Parkinson's disease (68%; Wood, Bilclough, Bowron, & Walker, 2002). Falls are not only a deterrent to the re-learning of walking but also can lead to re-hospitalization due to further health complications such as fractures. About 4 to 18% of fallers sustain serious injuries such as fractures (Jorgensen et al., 2017) and 45% report reduced community participation and engagement in productive activities (Brotherton et al., 2007). Similar to older adults (Friedman, Munoz, West, Rubin, & Fried, 2002), falls can lead to a vicious circle of injuries, fear of falls, reduced activity participation, reduced functional levels, and higher incidence of falls. Individuals with a history of recurrent falls, fear of falling, and a slower walking speed have higher chances of experiencing recurrent and injurious falls (Jorgensen et al., 2017). A majority of falls occur during walking (76%) (Phonthee, Saengsuwan, & Amatachaya, 2013). Most fallers perceive that limitations in muscle strength, balance control, and an inability to overcome environmental hazards lead to falls (Brotherton et al., 2007; Phonthee et al., 2013), suggesting factors internal and external to the individual are responsible for falls. Identifying individuals with SCI at risk of falls thus requires a comprehensive understanding of balance control in this population. Balance control not only depends on the functional level of these individuals, but also on the strategies they use when faced with an external perturbation.

1.3 Balance Control: An Important, But Complex Motor Skill

Stability, balance, balance control and postural control are defined in a variety of different ways (including mathematical, mechanical, and clinical) and have been used interchangeably in the literature. For the scope of this thesis, the concepts of balance, stability, balance control, and postural control are explained. Balance is an instantaneous state of the body when the vertical projection of the center of mass (COM; an average position of all the parts of the body weighted according to their masses) falls within the base of support (BOS; area of support formed beneath an object or person that includes all points of contact) (Pollock, Durward, Rowe, & Paul, 2000).

A body is stable if, due to the net forces acting on the body, it is moving from a state of unbalance to a balanced state or it resists becoming unbalanced from a balanced state. Stability takes into consideration time and net forces acting on a body, whereas balance is an instantaneous state (Loubert, 2011). For example, during walking the COM may be within the BOS indicating a balanced state, but the velocity dependent COM (extrapolated COM; XCOM; (Hof, Gazendam, & Sinke, 2005) may be outside the BOS, making a body unstable. Stability can be quantified in a variety of ways such as displacement of the COM and/or time available before the COM leaves the BOS (Hof et al., 2005), or the amount of force needed to unbalance an object which is currently in a state of balance (destabilizing forces), or to balance an object which is about to lose balance due to non-zero forces acting on it (stabilizing forces; Duclos et al., 2009). The margin of stability (MOS) is another measure of stability, which is often defined as the distance between the COM or XCOM and the edge of the base of support (Hof et al., 2005). Similarly, the temporal stability margin is the time in which the COM would reach/exceed the boundary of the BOS travelling at its current velocity (Hof et al., 2005).

Balance control or postural control in humans are synonymous terms and are used interchangeably here indicating the inherent ability of an individual to maintain, achieve or restore a state of balance during any posture or activity (Pollock et al., 2000). An individual with intact balance control should be able to resist any perturbations or should be able to generate stabilizing forces once the perturbation(s) has(have) occurred. From a biomechanical perspective, this is achieved by maintaining the COM (or XCOM during dynamic conditions) within the BOS while performing activities of daily living (Maki & McIlroy, 1997). From a

motor control perspective, it is a complex motor skill, which is dependent on how the motor and sensory systems of an individual interact with the environment to achieve the task being performed such as sitting, standing, walking, or transferring (Horak, 2006).

1.3.1 Balance control for intact body systems.

The Systems Framework for Postural Control suggests six essential resources are required for effective postural control: (1) sensory strategies (e.g. integration between somatosensory, visual, and vestibular systems), (2) orientation in space (e.g. aligning the body to gravity on a tilted surface), (3) movement strategies (e.g. taking a compensatory step on perturbation), (4) biomechanical constraints (e.g. range of motion, muscle strength, etc.), (5) dynamic balance control (e.g., walking balance), and (6) cognitive processing (e.g. dividing attention to performing multiple tasks simultaneously) (Horak, 2006). All of these resources are inter-related and may not be mutually exclusive in terms of effective postural control. This thesis focuses primarily on the sensory integration, movement strategies, and control of dynamic aspects of balance control, and thus the remaining section will focus on these three areas.

Sensory integration. Different sensory systems, including the somatosensory, visual, and vestibular systems, interact to provide orientation of the body in three-dimensional space. During quiet standing on a stable surface with eyes open, the major contribution in terms of postural orientation is provided by somatosensory cues (70%), followed by vestibular (20%) and vision (10%); however, with impairments in any one of the sensory systems or a change in task conditions, an individual needs to re-weight the contribution of each system to maintain balance control (Peterka, 2002). For example, in the presence of somatosensory impairments, a greater reliance is seen on the visual system in patients who have had a stroke in order to maintain balance control (Bonan et al., 2004). Another way to improve balance control in individuals with sensory impairments can be by providing additional sensory input about the body's orientation in relation to surroundings through an intact sensory system. Haptic input, which involves sensory input from fingertip contact forces and proprioception in the arms while touching a stable object (such as a rail, or anchors which are small weights attached to a cord) fixed in the environment, can be one of the ways to improve balance (Holden, Ventura, & Lackner, 1994). Haptic input in form of light touch has shown to improve standing balance in AB individuals (Holden et al., 1994), and individuals with neurological impairments such as stroke (Cunha, Alouche, Araujo, &

Freitas, 2012) and Parkinson's disease (Franzen, Paquette, Gurfinkel, & Horak, 2012). Haptic input has also shown short term positive effects on balance such as reduction in variability of gait steps and stability (Hedayat, Moraes, Lanovaz, & Oates, 2017; Oates, Hauck, Moraes, & Sibley, 2017).

Dynamic balance control during walking. Dynamic balance control during tasks such as changing one's posture and walking is more challenging than quiet standing. Balance control during quiet standing can be achieved by controlling the center of pressure (COP; the point of application of vertical ground reaction force) within the BOS using lower extremity muscles (e.g. ankle plantarflexors and dorsiflexors, or hip abductors) to keep the COM within the BOS; however, during dynamic tasks such as walking, balance control becomes more complex (Winter, 1995). During walking, the COM is intentionally moved outside the BOS and steps are taken to change the size and position of the BOS in order to catch the falling COM. Safe walking, in addition to generating alternate and rhythmic stepping movement, requires an ability to maintain effective balance control.

According to the neural control model, a safe walking function is controlled by an interrelationship of a tripartite system consisting of neural circuitry between specialized spinal neurons, supraspinal centres, and sensory feedback from the muscles and skin (Barthélemy et al., 2011; Zehr, 2005). There are specialized interneurons – CPGs within the gray matter of spinal cord that can generate an organized alternate rhythmic pattern (Rossignol & Frigon, 2011); however, for balance control these CPGs require input from supraspinal centres such as the brain stem, motor cortex and cerebellum, and peripheral skin and muscle sensory receptors (Barthélemy et al., 2011; Zehr, 2005). The CPGs receive inputs from the supraspinal centres through various tracts including reticulospinal, vestibulospinal, and corticospinal tracts (Rossignol & Frigon, 2011). In animal models, through their contributions to the CPG, reticulospinal and vestibulospinal tracts have shown an important role in initiating locomotion and balance control, whereas corticospinal tracts are shown to be involved in goal directed aspects of walking (Rossignol & Frigon, 2011). In humans, corticospinal tracts have shown to be involved during normal walking using methods such as functional imaging of the brain, near-infrared spectroscopy, transcranial stimulation, etc.(Barthélemy et al., 2011). For example, activation of inhibitory mechanisms of motor cortex using transcranial magnetic stimulation has

been associated with suppression of muscle activity in the legs and arms during walking (Petersen et al., 2001). Similarly, sensory feedback in the form of electrical stimulation in animal models has shown to modulate changes in walking function through its interaction with CPGs (Field-Fote, 2004; Forssberg, Grillner, & Rossignol, 1977). In humans, sensory input in form of electrical stimulation and whole body vibration has shown to modify the CPGs involved in walking (Field-Fote, 2004; Gurfinkel, Levik, Kazennikov, & Selionov, 1998; Ness & Field-Fote, 2009).

Movement strategies. Balance control also depends on the movement strategies adopted by the individual, which are related to the biomechanical constraints (BOS, muscle strength, range of motion, etc.) and objectives of the task (standing, walking, recovering from a slip, or negotiating obstacles). External perturbations (such as slips and trips) add to the challenge of balance control, and require proactive or reactive strategies depending on the knowledge of perturbation. An individual may develop proactive strategies if there is knowledge of an impending perturbation, for example walking slower, with shorter steps and flatter foot-floor angle in anticipation of a slippery surface (Marigold & Patla, 2002). If a perturbation is unexpected, the strategy used to regain balance is called a reactive strategy, such as a quick onset of muscle activation, swinging of the arms, or taking a quick compensatory step in response to an unexpected slip (Chambers & Cham, 2007; Marigold & Patla, 2002). Reactive responses result from activation of the peripheral nervous system by a perturbation, and can be mediated at the level of spinal reflexes or can involve higher centres (Barthélemy et al., 2011). Responses involving higher centres are slower than reflex responses but are functionally more relevant (Patla, 2003). Proactive balance control is a feed-forward control strategy originating in the central nervous system, and is dependent on visual input and knowledge of prior experience with the potential perturbation (Barthélemy et al., 2011; Patla, 2003). Proactive strategies have been shown to require the involvement of the higher centres (such as the brain stem, cerebellum, or motor cortex (Barthélemy et al., 2011).

Impairments in the sensory system limit the availability of information about the body's orientation in space, which can interfere with accurate estimation of the response by the central nervous system to overcome any perturbation. An inability to generate effective motor responses can also limit the ability to prepare for or to react to perturbations. When there is a limitation in

availability of motor and sensory resources, such as after a SCI, individuals need to adopt strategies which are specific to the context of environment and task to maintain stability or else a perturbation can lead to a fall.

1.3.2 Balance control after a spinal cord injury.

Sensory integration. Depending on the location of a lesion, a SCI can impair different sensations such as touch, pressure, and/or proprioception. Limited information from the somatosensory system imposes a greater reliance on unimpaired resources such as vision for balance control. During quiet standing, an increase in postural sway is observed in individuals with iSCI as compared to AB individuals when eyes are closed, indicating a greater reliance on vision by individuals with SCI (Lemay et al., 2013). Similarly, during walking, individuals with iSCI rely more heavily on vision to cross obstacles as indicated by the adoption of compensatory strategies to perform the task when vision is obstructed (Malik, Cote, & Lam, 2017). This shows the potential of individuals with iSCI to re-weight the available sensory information and use it for balance control during tasks such as standing or walking and negotiating one's environment. It is not known if a reliance on vision can help these individuals to maintain balance control during more complex tasks such as stepping over large obstacles or during unexpected perturbations. Furthermore, the effect of additional sensory input, such as haptic input using light touch, on balance control has not been investigated in individuals with SCI.

Dynamic balance control during walking. Previous literature has shown that individuals with chronic iSCI are more stable than AB individuals during normal walking (Day, Kautz, Wu, Suter, & Behrman, 2012; Lemay, Duclos, Nadeau, Gagnon, & Desrosiers, 2014). A greater amount of force is required to destabilize individuals (destabilization force) with iSCI by moving their COP to the boundary of the BOS during the single stance support phase of gait as compared to AB individuals (Lemay et al., 2014). Similarly, individuals with chronic iSCI require a smaller amount of force to maintain stability (stabilization force) by stopping both the COP and the COM from going outside the BOS (Lemay et al., 2014). The need of greater destabilization forces and smaller stabilization forces suggest greater stability during walking (Duclos et al., 2009). Greater stability among individuals with chronic iSCI may be due to walking at a slower speed (Lemay et al., 2014). One of the possible explanations for adopting a slower walking velocity can be to accommodate the limitations in sensori-motor impairments

and to avoid a loss of balance during normal walking (Lemay et al., 2014). It is not clear to what extent the greater walking stability achieved by walking slower protects individuals with iSCI from external perturbations such as unexpected slip.

Movement strategies. On unexpected surface translations during standing, individuals with chronic iSCI show an increase in the magnitude of leg muscle activation, similar to AB individuals, indicating effective reactive control (Thigpen et al., 2009). Although individuals with iSCI had slower onset of tibialis anterior and soleus muscle during expected and unexpected perturbations as compared to AB individuals, the movement responses were adequate for maintaining balance control (Thigpen et al., 2009). Both individuals with chronic iSCI and AB individuals also show quick (within 1-2 trials) adaptation to repeated perturbations during standing indicating good proactive adaptations leading to a smaller increase in leg muscle activity upon subsequent perturbations (Thigpen et al., 2009). The reactive responses during standing cannot be generalized to that during walking as the mechanisms governing standing and walking stability are different (Kang & Dingwell, 2008); however reactive balance during walking has not been studied in individuals with SCI.

1.4 Assessment of Balance Control in Individuals With iSCI

Despite the high incidence of falls among individuals with SCI, there is a limited understanding of balance control in this population. Since balance control consists of different domains, it is essential to identify measures that can provide an accurate and comprehensive assessment of balance control to identify individuals at risk of falls. According to the Systems Framework for Postural Control, balance control involves a complex interaction of multiple systems, along with the task(s) and the environment (Horak, 2006). To identify individuals at risk of falls, the assessment of balance should be comprehensive (Sibley, Beauchamp, Van Ooteghem, Straus, & Jaglal, 2015). Furthermore, the assessment of balance control needs to be psychometrically-sound. A measure with sound psychometric properties means the measure has established validity (i.e. it measures what is intended to measure), reliability (i.e. it consistently yields the same findings), and responsiveness (i.e. the measurement scores change with change in the construct being measured) (Roach, 2006). Psychometric properties are specific to the population (Roach, 2006); therefore, the measures that have sound psychometric properties for measuring balance in populations other than SCI, may not be valid in individuals with SCI. A

balance measure should have clinical utility if it is to be used in clinical environments. Clinical utility means the measure should be cost effective, quick and easy to administer (Tyson & Connell, 2009). In clinical settings, there is a paucity of information regarding what measures are available and appropriate for assessment of balance in the SCI population.

There are over 50 measures validated for the assessment of balance in clinical environments for adult populations (Sibley et al., 2015). The measures that are used to evaluate balance in SCI are unknown; however, the Rick Hansen Institute's SCI Standing and Walking Toolkit (Verrier, Gagnon, & Musselman, 2017) and the American Physical Therapy Association's Evaluation Database to Guide Effectiveness (EDGE) task force (Kahn et al., 2016) have suggested some measures for the SCI population such as the Berg Balance Scale (BBS), Functional Reach Test (FRT), Timed Up and Go (TUG), Activities Specific Balance Confidence Scale (ABC), Spinal Cord Injury Functional Ambulation Profile (SCI-FAP), Mini-Balance Evaluation Systems Test (MiniBESTest), 6-Minute Walk Test, and 10-meter Walk Test. Three of these measures are generally accepted to measure balance control – BBS, FRT, & mini-BESTest. It is likely that a greater number of balance measures have been used with individuals with SCI, and need to be identified through systematic searching.

In summary, there are gaps in the literature regarding the understanding of balance control in individuals with SCI and the assessment of balance in this population. The studies that will be carried out for this thesis address some of these gaps. The next four chapters of this thesis will focus on the: (1) effect of haptic input on standing balance in individuals with iSCI; (2) walking stability during normal walking and its association with slip intensity following an unexpected slip perturbation among individuals with an iSCI; (3) reactive responses following an unexpected slip perturbation in individuals with iSCI; and (4) current state of balance assessment among individuals with SCI.

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CHAPTER TWO: EFFECT OF HAPTIC INPUT ON STANDING BALANCE AMONG INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

(Arora, T., Musselman, K. E., Lanovaz, J., & Oates, A. (2017). Effect of haptic input on standing balance among individuals with incomplete spinal cord injury. *Neuroscience Letters*, *642*, 91–96. https://doi.org/10.1016/j.neulet.2017.02.001)

2.1. Introduction

Seventy-five percent of individuals with incomplete spinal cord injury (iSCI) report at least one fall a year (Brotherton, Krause, & Nietert, 2007) and most of the falls in this population are reported while standing and walking (Amatachaya, Wannapakhe, Arrayawichanon, Siritarathiwat, & Wattanapun, 2011). Falls can lead to health complications, such as fractures, soft tissue injuries, a fear of falling, and subsequent restriction of activities and community participation (Amatachaya et al., 2011; Brotherton et al., 2007). Standing balance is also one of the major determinants of walking function in this population (Scivoletto et al., 2008); therefore, discovering effective strategies to improve standing balance in individuals with iSCI is important.

Standing balance is maintained by keeping the center of mass within one's base of support (BOS) by voluntarily moving the center of pressure (COP) (Hof, Gazendam, & Sinke, 2005). Characteristics of COP movement are commonly used measures of standing balance (Ruhe, Fejer, & Walker, 2010) and represent the complex interactions between visual, somatosensory, vestibular, and motor functions to maintain balance. Impairment in one system can lead to more reliance on the other systems. For example, individuals with iSCI show a greater reliance on vision for maintaining standing balance likely because of somatosensory impairments (Lemay et al., 2013).

One mechanism to improve standing balance can be through haptic input, which refers to the perception of sensory inputs from fingertip contact forces and proprioceptors in the arms while touching a stable object fixed in the environment (e.g., railing) (Holden, Ventura, & Lackner, 1994). During postural sway, mechanoreceptors located in the fingertip sense the shear forces between the finger and the touched object, whereas proprioceptors sense the change in configuration of the arm relative to the torso (Holden et al., 1994). The CNS uses this added

sensory information to reduce the postural sway. The amount of mechanical support using light touch (< 1N) can reduce body sway by only about 2.3% (Holden et al., 1994), which is considerably less than the reductions in body sway seen with light touch in AB individuals, individuals with balance disorders due to aging (Baccini et al., 2007), Parkinson's disease (Franzen, Paquette, Gurfinkel, & Horak, 2012) and stroke (Cunha, Alouche, Araujo, & Freitas, 2012). These findings suggest that the improvements in postural control are due to mechanisms other than mechanical support. In fact, the spatial information provided by the light touch can improve postural stability by as much as vision (Holden et al., 1994).

In individuals with iSCI, haptic input in form of light touch may improve standing balance by compensating for the sensory deficits in the lower extremities (LE); however, the extent of improvement may depend on the magnitude of somatosensory impairments in the upper extremities (UE) and LE. Loss of cutaneous and/or proprioceptive information in the UE may negate the effect of added haptic input as the individual will not perceive relevant information; whereas, individuals with greater sensory loss in the LE may benefit more from additional sensory information in the form of light touch as the added UE sensory input can be used in place of the reduced LE input. The effect of light touch on standing balance of individuals with iSCI has not been studied. Furthermore, the relationship between the extent of impairment in somatic sensation and the effect of light touch has not been studied; therefore, the objectives of this study were to: (a) investigate the effect of light touch on the standing balance of individuals with iSCI; (b) understand the relationship between the effect of light touch and UE and LE proprioception, and cutaneous pressure sensation. We hypothesize that individuals with iSCI will: (a) show a reduction in quiet standing postural sway with light touch, and; (b) show a significant correlation between the effect of light touch and clinical measures of cutaneous pressure and proprioception in LE and UE.

2.2. Methods

2.1.1. **Participants.**

Participants with iSCI were recruited from regional health centres and advertisements within the province of Saskatchewan. Individuals who were at least one-year post iSCI, classified as American Spinal Injury Association Impairment Scale (AIS) C or D, and who were able to stand independently for sixty seconds were included in the study. Participants were

excluded if they had any other disease, injury, or condition that could have affected standing balance. Age (±3 years) and gender matched healthy AB participants were recruited from the local community through advertisements. This study was approved by the University of Saskatchewan Biomedical Research Ethics Board.

2.1.2. **Experimental procedure.**

Participants were asked to stand for 60 seconds on a force platform mounted flush with the floor (18.25 x 20 inches, AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA) under each of the four conditions in the following order: (i) eyes open no touch, (ii) eyes closed no touch, (iii) eyes open touch, (iv) eyes closed touch. The eyes closed condition is more challenging and discriminating than eyes open condition, and also it can affect the validity and reliability of COP measures (Tamburella, Scivoletto, Iosa, & Molinari, 2014), therefore the eyes closed condition was included in this study. Participants stood with their shoes on and with their feet at a self-selected comfortable position. For the touch conditions, participants lightly touched a rail with the tip of their dominant index finger (self-reported). The rail was set on the same side as their dominant hand at a standard height of 85 cm above and parallel to the walking surface such that the participants received haptic input from the lateral side. The rail was instrumented with force sensors (Futek LRF400, Advanced Sensor Technology, Inc., Irvine, CA) to measure the amount of vertical touch force in Newtons (N). Before each trial, participants were instructed to use less force if they were applying more than 1N of force during the previous trial. If a participant had UE sensory and/or motor impairments, he/she used the index finger of the less affected side to touch the railing, as determined by their cutaneous pressure sensation and proprioception scores (iSCI only).

Kinematic data were obtained using a 3D motion capture system (Vicon Nexus, Vicon Motion Systems, Centennial, CO). Base of support (BOS) was calculated from markers at three locations on each foot – heels, tips of first toe, and the most lateral part of the foot at the base of the fifth metatarsals. Cutaneous pressure sensation was tested using monofilaments (Baseline® Tactile™ Monofilaments) of six different thicknesses for the palmar surface of the index finger on the touch side, and for the plantar surface of the first toe bilaterally. The monofilaments were applied in order of descending thickness. With the participant's eyes closed, a researcher applied

each monofilament six times. Participants were instructed to say 'yes' if they could feel pressure being applied. A score of one was assigned for each correct 'yes' response, leading to a total possible cutaneous pressure score of 36 for the UE and 72 for both LE combined. Proprioception was measured in the touch side upper extremity in the following order - metacarpo-phalangeal, wrist, elbow, and then shoulder joints on the touch side, and in both lower extremities at the first metatarso-phalangeal and ankle joints. The same researcher moved each joint slowly through approximately 10 degrees of extension (plantarflexion) or flexion (dorsiflexion) six times. Participants were asked to state the direction of movement (up or down) with their eyes closed (Gilman, 2002). A maximum score of six for each joint was recorded, leading to a total possible proprioception score of 24 for the UE, and 24 for both LE combined. To describe ambulatory status, scores on the Walking Index for Spinal Cord Injury (WISCI II) were also obtained. The WISCI II is a 21-item scale of walking capacity that ranks walking according to the amount of physical assistance, braces and walking aids required (Dittuno & Ditunno, 2001).

2.1.3. **Data analysis.**

The force platform and 3D kinematic data were collected at sampling rates of 2000 Hz and 100 Hz, respectively. The force platform data was filtered at 10 Hz using a 4^{th} order low pass Butterworth digital filter (Ruhe et al., 2010). Custom MATLAB (R2006b for PC, MathWorks, Natick, MA) routines were used to obtain COP and BOS data. The following measures of COP sway were used as indicators of standing balance: (1) medio-lateral root mean square (RMS_{ML}), (2) antero-posterior root mean square (RMS_{AP}), (3) medio-lateral mean velocity (Vel_{ML}), (4) antero-posterior mean velocity (Vel_{AP}), (5) area of an ellipse, centered at the mean, encompassing ninety percent of COP samples (Area90%), (6) length of medio-lateral radius of the ellipse (Rad_{ML}), and (7) length of antero-posterior radius of the ellipse (Rad_{AP}). Root mean square measures are indicators of variability of COP distribution, whereas velocity and area measures are indicators of change in COP position with time and the amount of sway, respectively. Since, the feet position was determined by the comfort level of the participants and was not fixed, the COP measures were normalized to the individual's BOS: RMS_{ML} and Rad_{ML} measures were normalized to the width of BOS, and RMS_{AP} and Rad_{AP} measures were normalized to the length of BOS, and Area90% was normalized to the area of BOS. These COP

measures are shown to be reliable and valid for individuals with iSCI (Tamburella et al., 2014), as well as for AB individuals and individuals with other health conditions (Ruhe et al., 2010).

2.1.4. **Statistical analysis.**

Means, standard deviations, and ranges were obtained for participant characteristics. Independent *t*-tests were used to look at the differences in age, mass, height, and touch force between the iSCI and AB groups. Repeated measures ANOVA was used to compare average touch forces between conditions (eyes open and closed) and groups (iSCI and AB). A two-way mixed design MANOVA was used to test the effects of touch, vision, and group on the COP measures. Touch (no touch and light touch) and vision (eyes open and closed) were used as within-subject factors, and group (iSCI or AB) was used as a between-subject factor. Scheffe's test was used for post-hoc analysis.

In order to investigate the effect of haptic input on COP movement, differences in each COP measure (ΔCOP) were calculated for touch and no touch conditions such that ΔCOP = (COP during No Touch Condition) – (COP during Touch Condition) and a positive ΔCOP would be a positive effect indicating an increase in stability. Pearson's correlation analysis was used to determine the relationship between the ΔCOP for each measure and proprioception and cutaneous pressure scores in the UE and LE extremities for the participants with iSCI only. Correlation analyses were performed separately for the eyes open and eyes closed conditions. Alpha was set at 0.05 for all the tests. All statistical analyses were performed using IBM SPSS (IBM SPSS Statistics, Version 22).

2.3. Results

Sixteen individuals with iSCI (13 males; 61.1 ± 19.9 years) and 13 AB individuals (10 males; 59.4±19.7 years) participated. Participant demographics are shown in table 2.1. Participants with iSCI either had injury from a traumatic (n= 14), or non-traumatic cause (n = 2). Eight participants had injuries leading to tetraplegia and all were AIS D impairment level with the exception of one participant with an AIS C impairment level.

Table 2.1

Mean characteristics of the iSCI participants

Participants' Characteristics	SCI (n=16)		AB (n=13)	
	Mean ± SD	**Range**	**Mean ± SD**	**Range**
Mass (kg)	82.36 ± 19.94	60.20 - 131.0	81.10 ± 18.17	58.80 - 120.8
Height (m)	1.74 ± 0.12	1.50 - 1.92	1.76 ± 0.10	1.57 - 1.88
Sex (Male : Female)	13 : 3	-	10 : 3	-
Age (years)	61.1 ± 19.9	29.8 – 95.9	59.4 ± 19.7	29.2 - 94.1
Time Since Injury (years)	9.43 ± 11.12 (Median=6.40)	2.47 – 47.94	-	-
Tetraplegia: Paraplegia	8 : 8	C1 - L4	-	-
AIS C: AIS D	1 : 15		-	-
Traumatic: Non-Traumatic	14 : 2			
Cutaneous Pressure				
Unilateral Upper Extremity (/36)	24.88 ± 5.77	8 - 34	-	-
Bilateral Lower Extremity (/72)	29.38 ± 12.65	7 - 52	-	-
Proprioception				
Unilateral Upper Extremity (/24)	23.88 ± 0.50	22 – 24	-	-
Bilateral Lower Extremity (/24)	19.69 ± 4.94	6 – 24	-	-
WISCI II (/20)	17.88 ± 3.58	9 - 20		

All individuals with iSCI had near normal proprioception in the UE ranging from 22-24 (out of 24); whereas proprioception in the LE extremities ranged from 6-24 (out of 24). Cutaneous pressure in UE and LE ranged from 8-34 (out of 36) and 7-52 (out of 72), respectively. The mean (±SD) score of touch force was less than 1N for both groups for eyes open (iSCI = 0.63 ± 1.00 N; AB = 0.71 ± 0.90 N) and closed (iSCI = 0.80 ± 0.86 N; AB = 0.73 ± 0.86 N) conditions, and the differences between iSCI and AB individuals or between conditions were not significantly different ($p>0.05$). Comparison of groups for age, mass, and height using *t*-tests did not reveal any significant differences ($p > 0.05$). Figure 2.1 shows a typical COP displacement in the medio-lateral and antero-posterior directions for an AB individual and an individual with iSCI.

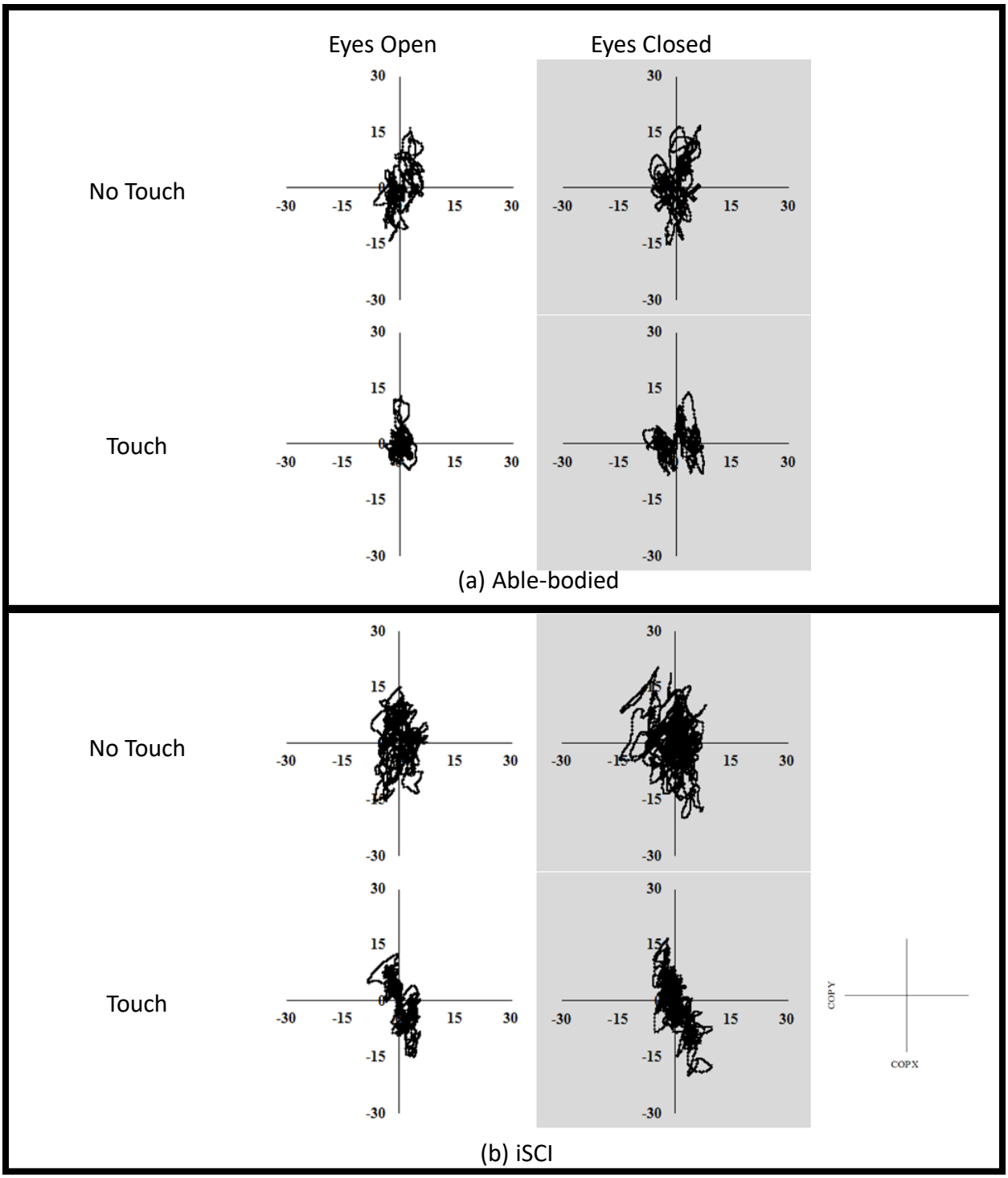
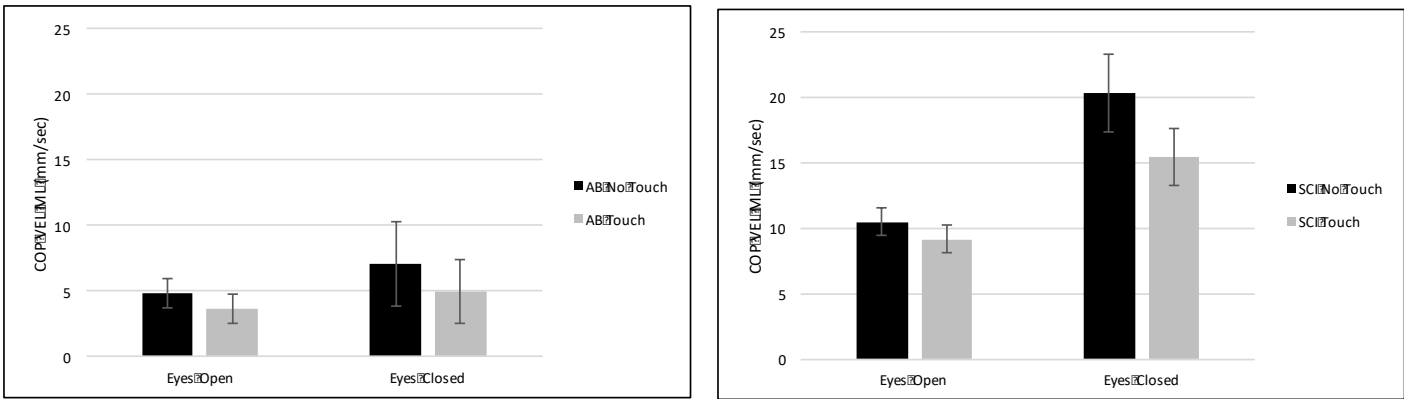


Figure 2.1. Typical COP displacements (in mm) during 60 seconds of quite standing in X (medio-lateral) and Y (antero-posterior) direction for age and gender matched (a) able bodied individual, and (b) individual with iSCI

Multivariate results revealed significant main effects for touch (F (7, 21) = 10.47, p < 0.001), vision (F (7, 21) = 8.31, p < 0.001), and group (F (7, 21) = 3.65 p = 0.01) (Table 2.2). Interactions were found to be significant between vision and group (F (7, 21) = 3.34, p = 0.015), but not for touch and group (F (7, 21) = 1.77, p = 0.147) (Table 2.2). Univariate results revealed significant main effects for touch, vision, and group for all seven COP measures indicating significantly higher values with (1) no touch condition, (2) eyes closed condition, and (3) for iSCI group. Figure 2.2 shows the group mean COP medio-lateral velocity values for all participants. During eyes open condition, AB and iSCI groups reduced COP velocity in ML direction on touch by 23.39% and 12.59%, respectively. The decrease in velocity with touch was greater during eyes closed conditions for both AB and iSCI groups – 29.87% and 24.05%, respectively. Interactions between vision and group were found to be significant only for RMS_{ML}, Vel_{ML}, Rad_{ML}, and Area90% (Table 2.3). Since the vision and group interaction was found to be significant only in ML direction, Figure 2.3 shows results of the variables in ML direction. There was greater increase in COP variability (50.9%), mean velocity (81.8%), and amount of sway (50.8%) in ML direction, respectively, with eyes closed in individuals with iSCI as compared to almost none (for variability and amount of sway) to a small (43.0% for mean velocity) change in AB individuals.



(a) **(b)**

Figure 2.2. Group COP mean velocity (Mean, SE) in ML direction for no touch and touch conditions for (a) able bodied individuals, and (b) individuals with iSCI for eyes open and eyes closed conditions

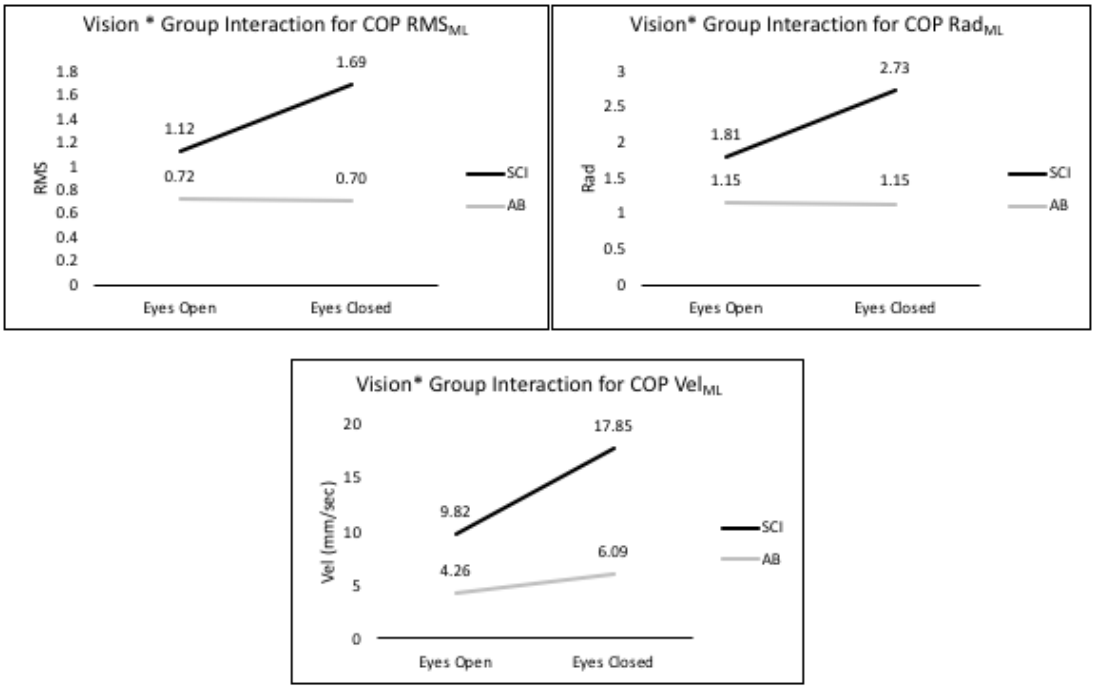


Figure 2.3. Significant interaction between vision and group for three COP measures in ML direction - COP RMS (variability of COP distribution), COP Rad (amount of sway), and COP Vel (change in COP position over time). RMS_{ML} and Rad_{ML} measures were normalized to the width of BOS.

For the eyes open condition, scores for proprioception and cutaneous pressure were not significantly correlated with ΔCOP for any measure. For the eyes closed condition, LE proprioception was found to have a significant, negative correlation with ΔCOP for RMS_{AP} (r = -0.712, p = 0.002) and Rad_{AP} (r = -0.659, p =0.005) (Table 2.4). UE cutaneous pressure was significantly positively correlated with ΔCOP for RMS_{AP} (r = 0.583, p = 0.018), Area90% (r = 0.555, p = 0.026), and Rad_{AP} (r = 0.546, p = 0.029) during the eyes closed condition.

Table 2.2

Repeated measures MANOVA multivariate results

	***F* (7, 21)**	***p***
Touch	10.47	<0.001*
Vision	8.31	<0.001*
Group	3.65	0.010*
Vision*Group	3.34	0.015*
Touch*Group	1.77	0.147

* Note. Significant at the p < 0.05 level.

Table 2.3

*Scheffe's post-hoc results for Vision * Group interaction*

COP Measure	*F*	*p*
RMS_{ML}	10.606	0.003*
RMS_{AP}	0.488	0.532
Vel_{ML}	6.187	0.019*
Vel_{AP}	4.174	0.051
Area90%	4.572	0.042*
Rad_{ML}	10.214	0.004*
Rad_{AP}	0.155	0.697

* *Note*. Significant at the $p < 0.05$ level.

Table 2.4

Correlation, r (p) Value Between ΔCOP and Lower Extremity Proprioception and Upper Extremity Cutaneous Pressure Sensation with Eyes Closed

	LE_Proprioception	UE_Cutaneous Pressure
UE_Cutaneous Pressure	-0.289 (0.277)	1
RMS_{ML}	-0.005 (0.984)	0.299 (0.260)
RMS_{AP}	-0.712* (0.002)	0.583* (0.018)
Vel_{ML}	-0.383 (0.144)	0.334 (0.206)
Vel_{AP}	-0.358 (0.173)	0.384 (0.143)
Area90%	-0.443 (0.086)	0.555* (0.026)
Rad_{ML}	0.054 (0.844)	0.251 (0.347)
Rad_{AP}	-0.659* (0.005)	0.546* (0.029)

* *Note*. Significant at the $p < 0.05$ level, *r*: Pearson's correlation coefficient, LE: Lower extremity, UE: Upper extremity, ΔCOP = COP measure calculated for No Touch Condition – COP measure calculated for Touch Condition

2.4. Discussion

The results of this study show that individuals with iSCI can reduce postural sway, and hence be more stable during standing, by adding haptic input through light touch. Overall, the reduction of postural sway with light touch in individuals with iSCI was found to be similar to AB individuals; however, individuals with iSCI showed a greater increase in postural sway with eyes closed compared to AB individuals similar to previous research (Lemay et al., 2013).

Results of this study are similar to the findings from studies on individuals with other neurological disorders such as Parkinson's disease (Franzen et al., 2012) and stroke (Cunha et al., 2012). Individuals with Parkinson's disease can use light touch to reduce their sway velocity (Franzen et al., 2012). Similarly, individuals who have had a stroke can reduce sway amplitude and velocity using light touch (Cunha et al., 2012). Reductions in sway in individuals with Parkinson's and stroke were not significantly greater than AB individuals (Cunha et al., 2012; Franzen et al., 2012). In our study, the interaction between group and touch was not significant indicating there was a similar reduction in postural sway in AB individuals and individuals with iSCI. As a reduction in sway is dependent on both the sensory feedback from the finger tips and arm orientation (Rabin, Bortolami, DiZio, & Lackner, 1999), it is possible that, in this study, participants with iSCI could not use light touch to reduce postural sway if there were impairments in UE cutaneous pressure sensation. Previous research has shown that after post-stroke hemiparesis, individuals who have had a stroke use somatosensory information from the unimpaired side more efficiently than the impaired side (Cunha et al., 2012). The positive relationship between cutaneous pressure sensation and ΔCOP for RMS_{AP}, Rad_{AP} and Area90% (Table 2.4) in our study confirms that those participants with iSCI who had better cutaneous pressure sensation showed a greater reduction in postural sway variability and amount of sway during the more challenging eyes closed condition.

Our study also found that LE proprioception was negatively correlated to the ΔCOP for RMS_{AP} and Rad_{AP} (Table 2.4) during the eyes closed condition. This indicates that participants with more significant impairments in LE proprioception used light touch to a greater extent to reduce postural sway variability and the amount of sway in the AP direction. These findings are unique as no other study has looked at the correlation between COP sway and lower extremity sensory scores in individuals with iSCI.

In AB individuals, fingertip contact beside the individual was previously found to be more effective during tandem (heel to toe) stance, and fingertip contact in front of the individual to be more effective during duck (heel to heel, toes-outward and knees-bent) stance (Rabin et al., 1999). In our study, individuals with iSCI showed a stronger correlation of UE cutaneous pressure and LE proprioception to improvements of sway in AP direction. Participants were also more unstable in the AP direction as indicated by higher mean COP values in the AP direction as

compared to the ML direction, and smaller length than width of the base of support. These findings suggest a greater use of light touch during a more complex (eyes closed) condition in a more unstable (AP) direction. Similar results were observed in previous research with individuals who have had a stroke; improvements were observed only in a more unstable (AP) direction when participants touched a laterally placed external surface with their paretic side, whereas, when the surface was touched with non-paretic limb, postural sway reduced both in the AP and ML directions (Cunha et al., 2012).

No significant correlations were found between UE proprioception and ΔCOP for any measure, which could be due to near normal UE proprioception in the participants. We found minimal deficits in UE proprioception in all participants, which could be because the clinical tools for measuring proprioception might not have been sensitive enough to capture slight impairments in proprioception (Suetterlin & Sayer, 2014).

Most participants were able to maintain a touch force less than 1N, but six of the participants (four for each condition) who had an iSCI could not maintain a mean level of force less than 1N. The level of touch was still less than 4N, which is similar to a previous study in individuals who had a stroke (Boonsinsukh, Panichareon, & Phansuwan-Pujito, 2009) suggesting that the level of touch in the current study is still considered "light". Unlike previous studies (Holden et al., 1994), the height of the rail was fixed in this study and could not be moved to each participant's comfort level; however, the railing was set at a standard building code height and was likely a familiar height to individuals.

In conclusion, individuals with iSCI improved their standing balance with light touch similar to AB individuals. Without vision, postural sway was reduced to a greater extent in individuals with more intact UE cutaneous pressure sensation and more impaired LE proprioception. In addition, individuals with iSCI seemed to rely more on vision for standing balance than AB individuals, confirming previous work (Lemay et al., 2013). Individuals with and without intact UE sensation responded differently to light touch suggesting that the level/extent of injury (i.e., tetraplegia or paraplegia) must be considered. The current findings suggest light touch has promise as an intervention for balance impairments in individuals with iSCI, and further research is warranted.

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RELEVANCE OF CHAPTER TWO TO THE THESIS

Sensory information about the body's orientation in space is essential for a balance control (Peterka, 2002). According to Systems Framework for Postural Control, the ability to weight and reweight sensory information from different systems and to put the available information to use is crucial for balance control (Horak, 2006). This study adds to the existing information on integration of visual and haptic information in form of light touch in individuals with chronic iSCI. Previous studies have shown that individuals with iSCI rely more on vision during quiet standing (Lemay et al., 2013) and walking (Malik et al., 2017). Our study confirmed the greater reliance on vision during quiet standing in individuals with iSCI, and also established that individuals with iSCI can benefit from additional haptic input in the form of light touch during quiet standing. This study also examines the relationship between improvements in standing balance and upper and lower extremity sensation and show that people with greater lower extremity impairments can benefit (i.e. show reduced postural sway) more if they have intact sensation in the area where additional haptic input is added. This information opens up avenues for studying the effects of light touch during walking balance and designing strategies to provide additional sensory input for improving balance in individuals with iSCI.

CHAPTER THREE: WALKING STABILITY DURING NORMAL WALKING AND ITS ASSOCIATION WITH SLIP INTENSITY AMONG INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

3.1 Introduction

The act of maintaining, achieving or restoring center of mass (COM) position relative to the base of support (BOS) during any posture or activity has been defined as balance control (Pollock, Durward, Rowe, & Paul, 2000). Damage to the spinal cord can disrupt sensorimotor and/or reflexive pathways leading to motor and sensory impairments contributing to diminished balance control and a high incidence of falls reported by individuals with incomplete spinal cord injury (iSCI). Approximately 75% of these individuals report at least one fall per year (Brotherton, Krause, & Nietert, 2007) while 48% report recurrent falls (Jorgensen et al., 2017). The consequences of falls can vary from minor injuries to severe complications requiring re-hospitalization and reducing functional community participation (Musselman, Arnold, Pujol, Lynd, & Oosman 2016; Krause, 2004). The high incidence and severity of falls warrant interventions that could improve balance control in people with iSCI.

Balance control is necessary for fall prevention, and is a complex motor skill that involves maintaining the COM within the BOS as well as the ability to increase the BOS if unable to maintain postural control (Hof et al., 2005). If the COM moves outside the BOS due to volitional movement or an external perturbation, it needs to be brought back within the BOS or a new BOS needs to be created to avoid falling. During dynamic conditions such as walking, balance control is even more challenging as it involves controlling a moving COM within the changing BOS (Patla 2003; Hof 2005). This precise motor skill relies on sensory feedback and impairments in the motor and sensory systems can challenge the ability to control balance. Under more challenging conditions – such as limitations in sensory feedback or an unstable external environment, individuals may adapt different strategies to achieve greater stability such as walking slowly, spending more time in double stance, walking with a flatter foot, or co-contracting the muscles to achieve greater stability in lower extremity joints (Chambers & Cham, 2007; Marigold & Patla, 2002). In able-bodied (AB) individuals, knowledge of an external slippery surface leads to such adaptive strategies, which helps them to reduce slip-fall potential (Chambers & Cham, 2007; Marigold & Patla, 2002).

In terms of forces required to stabilize or destabilize, individuals with iSCI may be more stable than AB individuals during normal unperturbed walking (Lemay et al., 2014). This greater stability is thought to be achieved from walking slower. Their walking also demonstrates an increased foot placement variability as compared to AB individuals which is thought to be a compensatory mechanism to avoid falling during walking (Day et al., 2012). It is still not known if individuals with iSCI demonstrate other strategies to increase stability, such as walking with shorter and wider steps, larger stability margins, a flatter foot at heel strike, or increased muscle co-contraction during unperturbed conditions. It is also not clear to what extent the increased stability during unperturbed walking may help individuals with iSCI avoid external perturbations such as unexpectedly stepping on a slippery surface.

Limited knowledge about balance control during walking among individuals with iSCI constrains our ability to develop effective interventions for this population. The objectives of this study were to: (1) compare balance control of individuals with iSCI to individuals without iSCI during normal unperturbed walking; and (2) to study the relationship between stability during normal unperturbed walking and slip intensity during a subsequent unexpected slip perturbation. We hypothesized that (1) measures of balance control during normal walking will show a greater stability among individuals with iSCI as compared to AB individuals; and (2) walking stability will be significantly correlated to slip intensity in individuals with iSCI such that a greater stability will be associated with a less intense slip.

3.2 Methods

3.2.1 Participants.

Adults with chronic iSCI (i.e. more than one-year post-injury) were recruited through regional health centres, the University of Saskatchewan, the provincial physical therapy association, and Spinal Cord Injury Saskatchewan. Individuals were included if their injury was classified as American Spinal Injury Association Impairment Scale (AIS) C or D, and who were able to walk 10 m without physical assistance from another person (walking aids and braces permitted). Participants were excluded if they had any other disease, injury, or condition that affected walking or balance ability (e.g. vestibular disturbance, joint pain, etc.). Age (± 3 years) and sex matched AB individuals were recruited from the local community through advertisements. This study was approved by the Institution's Research Ethics Board.

3.2.2 Data collection.

All participants were asked to walk unassisted without any walking aids (braces were allowed) at a self-selected speed for 10 m wearing comfortable shoes. Ten of the AB participants were also asked to walk at slower than their normal pace to more closely match their walking speed to that of individuals with iSCI. A slip device consisting of a set of low friction steel rollers (0.46 x 0.51 m; coefficient of static friction in unlocked state = 0.09) was embedded in the middle of the walkway, flush with the floor surface. For normal unperturbed walking (NW), the rollers were locked in place but could be unlocked to promote a slip in the antero-posterior (AP) direction. Participants were secured in a safety harness attached to a fall-prevention system, which did not limit any intended movement, and allowed free movement along the walkway. To avoid fatigue in participants with iSCI, no familiarization trials were included in the protocol. At least three normal walk (NW) trials in both iSCI and AB groups, and at least three slow walking trials in 10 AB participants were obtained with the slip device locked. Following the NW trials, the slip device was unlocked without the participant knowing to obtain one unexpected slip trial. After the slip trial, participants were asked if the slip was unexpected or not. For NW trials (self-selected and slow speeds), the last three trials before the unexpected slip were used and the middle 2-5 steps of each trial were analyzed to represent steady state walking and eliminate any gait initiation/termination behaviours.

Two force plates (0.46 × 0.51 m, AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA, USA) were embedded in the walkway (one under the slip device and the other diagonally adjacent to the slip device), which were used to collect GRF (fs = 2000 Hz) (Figure 3.1). A telemetered EMG (2400GT2, Noraxon Inc, Scottsdale, AZ, USA) system was used to collect surface EMG signals (fs = 2000 Hz) from tibialis anterior (TA) and soleus (SOL) muscles bilaterally. The lab was equipped with an eight-camera 3-D motion capture system (Vicon Nexus, Vicon Motion Systems, Centennial, CO, USA) that collected kinematic data at a sampling rate of 100 Hz. A marker set consisting of 63 reflective markers (14 mm diameter, 22 calibration and 41 non-calibration) were placed on the participant using landmarks. The marker set was used to collect kinematic information from 12 segments – head, trunk, and right and left upper arms, forearms, thighs, shanks, and feet. Kinematic data combined with anthropometric data for older (>60 years; Hanakova et al., 2015; Jensen & Fletcher, 1994; Pearsall, Reid, & Ross, 1994; Yeadon, 1990) and younger (de Leva, 1996) adults was used to calculate the

segmental and total body COM during walking trials. Total body extrapolated COM (XCOM) was calculated based on the velocity of COM (Young & Dingwell, 2012; Hof, Gazendam, & Sinke, 2005), and was used to calculate the margin of stability in the AP direction.

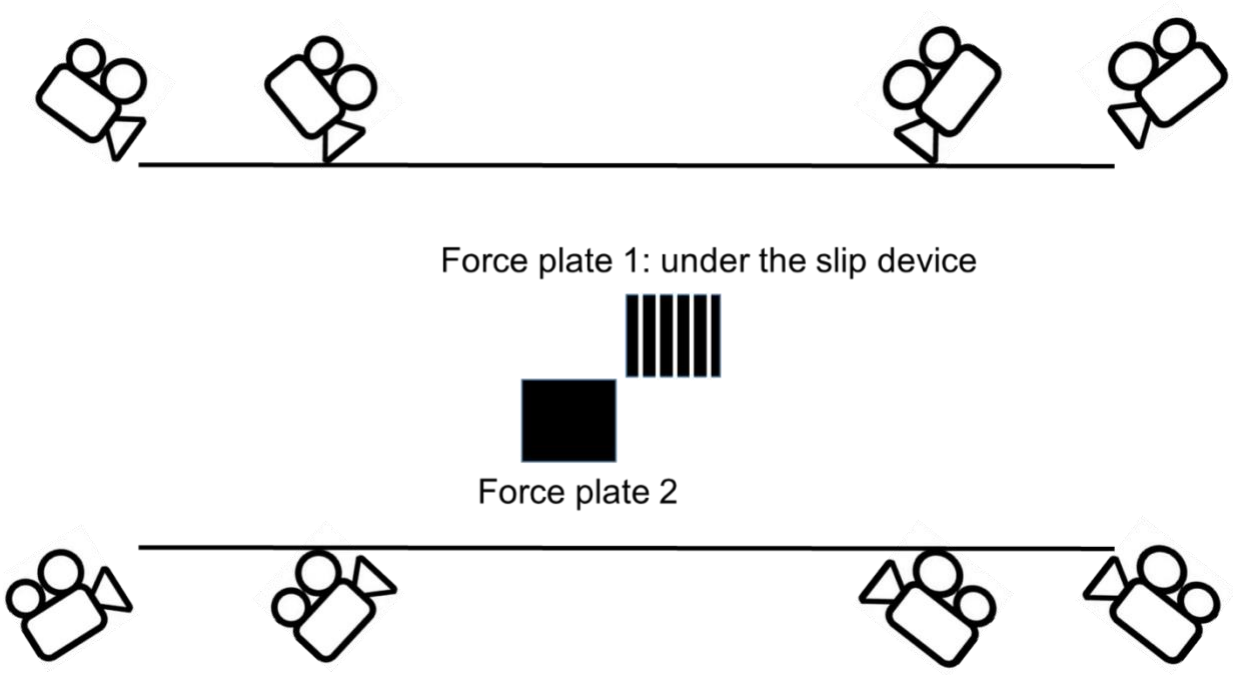

Figure 3.1. Schematic representation of the lab setting for data collection

In addition to the biomechanical measures, the 10-Meter Walk Test (10mWT) was administered to calculate self-selected and fast walking speeds (Bohannon, 1997; van Hedel, Wirz, & Dietz, 2005). For the self-selected 10mWT, participants were asked to walk at their preferred walking pace, whereas for the fast version of the test, participants were instructed to walk as fast as possible. Time(s) was recorded over the middle 10 m of a 14 m walkway, and speed (m/s) was calculated. Walking Index for Spinal Cord Injury II (WISCI II) scores were also obtained to describe ambulatory status. The WISCI II is a measure of walking capacity and consists of 21 items that rank walking according to the amount of physical assistance, braces and walking aids required (Ditunno et al., 2007).

3.2.3 Data analysis.

The following measures of walking stability were calculated from the self-selected and slow NW trials: (1) required coefficient of friction (RCOF), (2) co-contraction index (CCI), and (3) kinematic measures (i.e. margin of stability in the anterior-posterior plane (MOS_AP),

sagittal plane foot angle at foot contact, percentage of stride time in double support (%DS), average walking velocity, step length, and step width). For the unexpected slip trial, peak post-slip heel velocity (PSV) was used to determine the intensity of the unexpected slip, with a higher PSV indicating a more intensive slip. The foot contact and foot-off events of each gait cycle were identified using the resultant velocity signals from the heel and toe (Ghoussayni, et al., 2004; Bruening et al., 2014). The values obtained from the calculations were compared with the videos of several individuals and thresholds were adjusted in order to obtain consistent detections.

Required coefficient of friction. The RCOF value was calculated using the GRF signal. Raw GRFs were extracted from the steps in all NW trials that had a full foot contact on either force plate with either foot (confirmed by visual observation). Forces in the AP (Fy) and vertical (Fz) directions were low-pass filtered at 100 Hz using a 4th order Butterworth filter. The ratio of Fy to Fz signal at the time of the greatest posterior GRF (i.e. braking force) was used as the RCOF value.

Co-contraction index. The CCI was calculated using the EMG data from three NW trials. The raw EMG signal was full-wave rectified and low pass filtered at 10 Hz with a 4th order Butterworth filter. EMG data were obtained for each stance duration for all NW trials and normalized to the peak value of all NW trials (Figure 3.2). Ankle joint CCI was calculated using these peak normalized signals from TA and SOL muscles by integrating the signal obtained by multiplying the ratio of the less active to the more active EMG signal with the sum of both signals from -20% to +20% of average stance duration with 0% being foot contact (Chambers & Cham, 2007; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001):

$$\mathrm{CCI} = \int_{i=-20\%}^{i=20\%} \frac{\text{Less Active EMG}}{\text{More Active EMG}} \times (\text{EMG Less Active Muscle} + \text{EMG More Active Muscle})$$

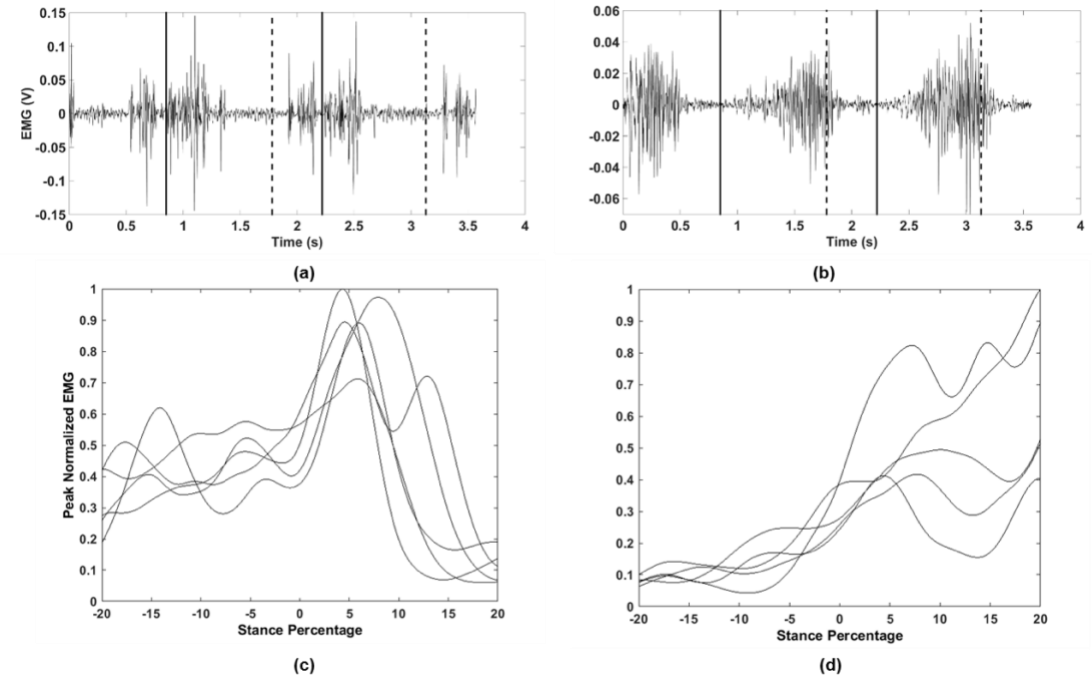

Figure 3.2. Raw EMG obtained during a typical NW trial of an AB participant from: (a) tibialis anterior (TA), and (b) soleus (Sol) with solid and dotted demarcation lines indicating beginning and end of stance, respectively. Filtered and peak normalized EMG activity around heel contact (0%) for each NW stance for a participant from (c) TA, and (d) Sol muscles. The co-contraction index (CCI) was calculated using (c) and (d).

Kinematic variables. Raw kinematic marker data were low-pass filtered at 8 Hz using a 4th order Butterworth filter before being used to calculate variables. Kinematic variables included average sagittal plane foot angle and MOS_AP at foot contact, and average walking velocity, %DS, step width, and step length throughout all NW trials.

Sagittal foot angle was calculated as the angle between the long axis of the foot formed by the ankle joint center and second metatarsal, and the horizontal. Average right and left foot angles at foot contact were obtained for all gait cycles. Preliminary statistical analysis revealed no significant differences between right and left foot angles so an average of right and left foot angles was used in analysis. The distance between the XCOM and the anterior foot boundary at foot contact on each side was averaged for each trial to obtain MOS_AP (Oates et al., 2008). The percentage of stance time with both feet on the ground over the entire stride was calculated to obtain %DS, which tells the proportion of time spent balancing on both legs during a stride, with

more time in double stance an indication of attempt to increase stability (Maki, 1997). Step width was calculated as the shortest distance between right and left heel markers at foot contact for each stride. Step length was calculated as the distance between right and left heel markers at the start of double support. Foot angles, MOS_AP, %DS, step width, and step length values obtained from all strides were averaged to obtain the final value. Walking velocity was obtained for each NW trial by differentiating the AP COM position with respect to time, and a mean value of three trials was calculated.

Post-slip heel velocity. Heel velocity was calculated by finding the derivative of the heel marker position with respect to time. The PSV was identified as the maximum anterior heel velocity of the slipping foot occurring after foot contact on a slippery surface before the foot came to a complete stop. Using a threshold of 1 m/s, slips were categorized as hazardous (PSV > 1m/s) or non-hazardous (PSV ≤ 1m/s) (Moyer, Chambers, Redfern, & Cham, 2006).

3.2.4 Statistical analysis.

Means, standard deviations, and ranges were calculated for participant characteristics. NW data were compared between three groups – (i) iSCI, (ii) AB at a self-selected speed (AB_SS), and (iii) AB at a slower speed (AB_slow). Assumption of normality of distribution of all the variables for iSCI and AB groups was tested using a Shapiro-Wilk test. Group differences were compared using multiple ANOVAs if the variables were normally distributed or else independent Kruskal-Wallis tests were used. If the differences were significant, follow-up independent *t*-tests or Mann-Whitney *U*-tests were carried out for parametric and non-parametric data, respectively. Demographics (including age, mass, and height) and measures of walking balance control were compared for significant differences between the iSCI and both AB groups. Self-selected and fast walking speeds of individuals with iSCI during the 10mWT were also compared for significant differences to assess if participants with iSCI had the potential to vary their walking speed.

Pearson's correlation coefficient was used to find significant correlations between PSV and the measures of walking stability if the variables were normally distributed or else Spearman's Rho coefficient was used. A chi-square test was used to compare the incidences of no slip, hazardous and non-hazardous slips between iSCI and AB groups. A conservative alpha

was set at 0.01 for all the tests due to the multiple comparisons. All statistical analyses were conducted using IBM SPSS (IBM SPSS Statistics, Version 24).

3.3 Results

Twenty individuals with iSCI (15 males; age: M=60.05, SD=17.77 years) and 16 AB individuals (12 males; age: M=58.92, SD=17.10 years) were included in the study. All individuals were able to walk independently without the need of assistive devices, indicating none of the participants with injuries below L1 had a flaccid paralysis that could impair walking. Ten of the 16 AB participants also walked at a slower walking velocity (8 males; age: M=51.99, SD=16.94 years). Although the slip device was visibly placed in the walkway, all participants reported the slip was unexpected, except one participant with iSCI, who was expecting a slip perturbation throughout the testing. One AB participant did not have a slip trial; therefore, the slip data for the AB group are from 15 individuals. Participant characteristics are shown in Table 3.1. Fourteen participants with iSCI had a traumatic injury including 11 with injuries leading to tetraplegia. All participants had an AIS D impairment level. Age, mass, and height were not significantly different between the two groups. Amongst individuals with iSCI, there was a significant difference between self-selected (M=1.00, SD= 0.29 m/s) and fast (M=1.38, SD=0.44 m/s) 10mWT speeds, (t (19) = -7.62, $p < 0.001$, n = 20), indicating they had the potential to walk faster than their self-selected speed.

Some of the walking stability measures in some participants could not be calculated due to error in the collected data (poor EMG signals, GRF, or kinematic data) leading to differences in numbers for each variable (Table 3.2). During NW trials, the number of steps that had a full foot contact on either of the force plates, ranged from two to ten for each participant. The GRF data from these steps were used for the calculation of RCOF.

Among measures of walking stability, Ankle CCI, walking velocity, MOS_AP, step width and step length were normally distributed and were compared using multiple ANOVAs. Average foot angle, %DS, and RCOF were not normally distributed and were compared using Kruskal-Wallis test.

Table 3.1
Mean characteristics of the iSCI and AB participants

Participant Characteristics	iSCI (n=20)		AB (n=16)	
	Mean (SD)	**Range**	**Mean (SD)**	**Range**
Mass (kg)	84.1 (19.4)	60.2 - 131.0	81.2 (16.0)	58.8 - 120.8
Height (m)	1.74 (0.11)	1.50 - 1.92	1.75 (0.09)	1.57 - 1.88
Sex (Male : Female)	15 : 5	-	12 : 4	-
Age (years)	60.1 (17.8)	29.8 – 95.9	58.9 (17.1)	29.2 - 94.1
Time Since Injury	8.6 (10.2)	2.01 – 47.9	-	-
(years)	(Median=6.4)			
Tetraplegia: Paraplegia	11: 9	C1 - L4	-	-
Traumatic: Non-Traumatic	14 :6			
WISCI II (/20)	Median = 20	17 - 20		

Note: WISCI: Walking Index for Spinal Cord Injury

Mean and standard deviation of the stability measures are shown in Table 3.2. For main effects, there were significant differences between the iSCI, AB_SS, and AB_slow groups for walking velocity, step length, AP_MOS, RCOF, average foot angle and %DS (Table 3.2). On follow-up tests, AB_slow group had a significantly smaller values for walking velocity, step length and average foot angle, and a significantly higher values for AP_MOS, RCOF and %DS than AB_SS group. The AB_slow group also had a significantly higher AP_MOS and a significantly smaller RCOF than the iSCI group. Individuals with iSCI had a significantly slower velocity and a shorter step length, and a significantly higher %DS as compared to AB_SS group.

The incidence of no slip, hazardous, or non-hazardous slips was not found to be significant on a chi-square test (χ^2 (2) = 3.61, p = 0.165); however, three individuals with iSCI did not slip when unexpectedly exposed to the slip perturbation. Thirty-five percent of individuals with iSCI (7/20) had a hazardous slip, and 50% (10/20) experienced a non-hazardous slip. In the AB group, all individuals experienced a slip; 60% (9/15) experienced a hazardous slip and 40% had a non-hazardous slip. Pearson (for normally distributed variables) and Spearman

(for non-normally distributed variables) correlation coefficients are reported in the table 3.3. Only average walking velocity during NW trials of individuals with iSCI was significantly correlated with the post-slip velocity on unexpected slip.

Table 3.2

Descriptive characteristics reported as Mean (SD), n, and independent t-test information for walking stability measures during normal walking in individuals with iSCI and AB individuals

Proactive Measure	SCI	AB_SS	AB_slow
Ankle CCI	13.0 (5.7), 19	12.7 (3.4), 13	12.6 (4.8), 9
Walking Velocity m/s*	0.68 (0.32), 19	0.95 (0.22), 16	0.42 (0.09), 10
MOS_AP, mm #	221.2 (61.4), 19	194.5 (79.2), 16	316.5 (32.4), 10
Step Width, mm	109.1 (44.5), 19	82.9 (38.6), 15	92.8 (35.9), 10
Step Length, mm *	482.1 (157.1), 19	608.5 (75.1), 15	425.6 (59.2), 10
RCOF #	0.11 (0.04), 19	0.14 (0.03), 14	0.08 (0.02), 9
Foot Angle, degree †	19.4 (9.0), 20	24.4 (3.8), 16	16.4 (3.5), 10
%DS *	42.2 (11.1), 19	33.7 (4.8), 15	46.7 (5.1), 10

Note: Significant differences (p <0.01) are indicated. * = AB_SS different from SCI and AB_slow; # = AB_slow different from SCI and AB_SS; † = AB_SS different from AB_slow

CCI: Co-contraction index; RCOF: required coefficient of friction; MOS_AP: antero-posterior margin of stability; %DS: percentage of time in double support.

Table 3.3

Correlation coefficients between peak post-slip heel velocity and walking stability measures

	iSCI		AB	
	Correlation Coefficient (p)	**n**	**Correlation Coefficient (p)**	**n**
CCI Ankle	0.48 (0.06)	16	-0.64 (0.03)	12
Walking Velocity	0.61 (0.01)*	16	0.39 (0.15)	15
MOS_AP	- 0.58 (0.02)	16	-0.28 (0.32)	15
Step Width	-0.37 (0.16)	16	-0.06 (0.82)	14
Step Length	0.56 (0.02)	16	0.16 (0.58)	14
RCOF#	0.47 (0.06)	17	0.39 (0.17)	14
Foot Angle#	0.53 (0.03)	17	0.20 (0.46)	15
% DS#	- 0.51 (0.04)	16	-0.11 (0.70)	14

Note: Significance level set at p = 0.01 and indicated with *. # Spearman Correlation Coefficient reported as data were not normally distributed. CCI: Co-contraction index; RCOF: required coefficient of friction; MOS_AP: antero-posterior margin of stability; %DS: percentage of time in double support.

3.4 Discussion

Individuals with iSCI experience frequent falls, with a majority of outdoor falls occurring while walking on an uneven or slippery surface (Jorgensen et al., 2017) warranting a deeper understanding of walking balance strategies used by these individuals. In this study, we confirmed that individuals with iSCI demonstrated a greater stability when walking at their self-selected speed by walking slower, with a shorter step length, and spending a longer percentage of time in double stance as compared to age and sex matched AB individuals. This greater stability was mediated by walking slower, as AB participants also demonstrated similar stability-related changes when walking at a slower speed. The magnitude of walking velocity for slow walking AB participants was 0.26 m/s slower than participants with iSCI. Although this difference was not statistically significant, a slower walking velocity contributed to more protection against an unexpected slip perturbation as indicated with a larger MOS, and a smaller RCOF among slow walking AB participants. Previous studies have also shown a greater stability during NW in individuals with iSCI to be mediated by walking slower (Lemay et al., 2014). In comparison with an AB population, individuals with iSCI required a lower stabilizing force for maintaining stability during NW by controlling the velocity of the center of mass, while greater destabilizing forces were required to perturb the individual by moving the center of pressure to the limit of base of support (Lemay et al., 2014).

Our study extended previous research to examine the effectiveness of this greater stability during NW in the prevention of hazardous slips. Walking velocity during NW in individuals with iSCI was found to have a moderate, but significant correlation with slip intensity, such that walking at a slower velocity was associated with less hazardous slips. There were no significant differences in the incidences of no-slip/hazardous/non-hazardous slips; however, all AB participants had a slip as compared to three participants experiencing no slip in iSCI group. Furthermore, a higher percentage of AB participants had hazardous slips indicating they are at a greater risk for hazardous slips when exposed to an unexpected slippery surface. In contrast to individuals with iSCI, AB individuals can rely on their intact reactive response to regain stability. Compared to AB participants, individuals with iSCI demonstrated greater stability during NW, which may be indicative of an avoidance to rely on their reactive responses that may be diminished due to sensori-motor impairments from their injury. Older individuals also demonstrate a greater walking stability by taking shorter and wider steps, walking slower, and

with a greater time in double stance during NW; however, the wider steps were found to be associated with a greater risk of falls (Maki et al., 1997). So, a greater stability during NW does not ensure that individuals with iSCI will regain stability once their balance has been perturbed but rather may indicate an increased risk of falling.

The slower velocity among participants with iSCI can also be due to lower functional levels. For example, in previous studies, individuals with iSCI were unable to lengthen their steps when needed to clear relatively large (4 cm and 8 cm long) obstacles suggesting functional limitations which is even more evident in individuals with lower functioning levels (incomplete tetraplegia vs. incomplete paraplegia, and AIS C vs AIS D) (Amatachaya et al., 2015; Amatachaya, Pramodhyakul, & Srisim, 2015). These reported functional limitations, however, are during a considerable challenge (stepping over relatively long and/or high obstacles) and not during normal, unobstructed walking conditions and so may not be evident in our testing protocol. In summary, individuals with iSCI are more stable during NW as they walk slowly, with shorter step length, and a greater percentage of time in double stance compared to AB individuals. Slower walking velocity during NW among individuals with iSCI was correlated with lesser slip intensity after an unexpected perturbation.

3.4.1 Limitations.

This study has a small sample size and some of the measures in some participants could not be calculated due to error in the collected data. To avoid fatigue among individuals with iSCI, no familiarization time with the laboratory set up and space was given to the participants, which may have affected the first few NW trials. To avoid any learning effect, the last three of all available NW trials before the unexpected slip perturbation were examined. Since all participants with iSCI had AIS D impairment level, the results of this study can only be generalized to individuals with iSCI who have high functioning levels. One participant with iSCI, who experienced a non-hazardous slip, reported anticipating the slip, which might have led him/her to develop strategies to achieve greater stability than if he/she was not expecting the slip. Slow walking AB participants were much slower than the participants with iSCI which limits our ability to distinguish velocity related versus balance related changes.

The slip device used for perturbation was relatively small and may have limited the amount of slip by stopping the sliding foot at the edge of the slip device; however, PSV was

reached at an average of 0.20 s, SD=0.08 s (range = 0.03 s–0.36 s) after foot contact, which is comparable to previously reported values for non-hazardous (M=0.12, SD=0.01 s) and hazardous (M=0.17, SD=0.03 s) slips on an oily surface (Cham & Redfern, 2002b). Poor reactive control among individuals with iSCI, which are not reported in this study, can be a contributor to the adoption of more stable walking and is currently being investigated in our laboratory. To ensure participants were as comfortable walking as possible, we asked them to wear shoes they were comfortable wearing which resulted in a variety of shoe types. We did not take into account the differences in the type of shoes (or soles) selected by the participants during walking in which may have affected the RCOF values and walking behaviours calculated (Li & Chen, 2004). We used a safety harness for fall prevention, which may have made participants feel more secure compared to walking without the harness and may have changed their walking behaviour.

3.5 Conclusion

Individuals with iSCI normally walk slower, with shorter step length, and with a greater percentage of time in double stance leading to more stable walking than AB individuals. The greater stability thus obtained by walking slower helps reduce the effect of unexpected perturbations as walking velocity correlated with the unexpected slip intensity among participants with iSCI. Despite greater stability during NW, individuals with iSCI experience a high incidence of falls highlighting the need to investigate reactive balance strategies in this population.

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RELEVANCE OF CHAPTER THREE TO THE THESIS

Individuals with chronic iSCI have shown to be more stable than AB individuals using a stabilizing and destabilizing force paradigm (Lemay et al., 2014). This study adds to the knowledge on dynamic control of balance among individuals with iSCI. Greater stability during walking was confirmed among individuals with iSCI, which was achieved by walking slower, with a shorter step length, and spending a greater percentage of the gait cycle in double stance. Walking slower helps individuals with iSCI in having a less hazardous slip as compared to AB individuals. It is not clear whether walking slower is due to functional limitations or due to avoidance of a fall. Similar strategies are reported in older individuals, which are found to be correlated with a fear of falling (Maki, 1997). Furthermore, the presence of such strategies does not necessarily ensure protection from falls as, once balance is perturbed, the ability to maintain balance depends on reactive balance control. The results of our study combined with the previous literature indicates that the presence of more stable walking may indicate a compensation for the impairments in other aspects of balance such as reactive balance control or the inability to generate postural adjustments to perform challenging tasks, which will be discussed further in the next chapter.

CHAPTER FOUR: REACTIVE RESPONSES FOLLOWING AN UNEXPECTED SLIP PERTURBATION IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

4.1 Introduction

Each year, approximately three-fourths of individuals with incomplete spinal cord injury (iSCI) experience at least one fall (Brotherton, Krause, & Nietert, 2007), while one half report recurrent falls (Jorgensen, Opheim, Halvarsson, Franzen, & Roaldsen, 2017). Half of these falls occur while walking outdoors, and the majority of outdoor falls occur while walking on an uneven or slippery surface (Jorgensen et al., 2017). Falls can lead to injuries, a fear of falling, and subsequent restriction of activities and community participation (Amatachaya, Wannapakhe, Arrayawichanon, Siritarathiwat, & Wattanapun, 2011; Brotherton et al., 2007), thereby lowering the quality of life of individuals with iSCI. Furthermore, the costs associated with SCI are an economic burden on the health care system (Krueger, Noonan, Trenaman, Joshi, & Rivers, 2013). The incidence of falls in the SCI population must be reduced in order to prevent fall-related injuries and associated healthcare costs. Impaired balance is a modifiable fall-risk factor (Musselman, Arnold, Pujol, Katie, & Oosman, 2018; Rose & Hernandez, 2010) so to reduce falls and fall-related injuries, there is a need for a better understanding of how these individuals control balance while walking.

Individuals with chronic iSCI tend to be more stable during unperturbed walking because they walk with a slower speed, with shorter steps, and a greater percentage of the gait cycle spent in double support (Arora et al., 2018). A greater amount of force is required to destabilize these individuals during normal walking suggesting greater walking stability, which is achieved by walking at a slower speed (Lemay, Duclos, Nadeau, Gagnon, & Desrosiers, 2014). Greater stability during normal walking may indicate that proactive balance strategies are used to mitigate threats to stability when faced with a perturbation (Arora, Musselman, Lanovaz, & Oates, 2017; Lemay et al., 2014; Maki, 1997). In contrast, we know little about reactive balance responses during walking in individuals with SCI. During quiet standing, when their balance is perturbed, individuals with iSCI and an American Spinal Injury Association Impairment Scale (AIS) rating of D showed adequate reactive responses to regain balance (Thigpen et al., 2009);

however, balance responses are context specific such that reactive responses during standing cannot be extended to that during walking (Shimada et al., 2003).

When exposed to an unexpected slip during walking, able-bodied (AB) individuals rapidly activate their lower extremity muscles, swing their arms, and take a compensatory step to regain stability and avoid a fall (Chambers & Cham, 2007; Marigold & Patla, 2002; Tang & Woollacott, 1998). Reactive responses should be scaled in magnitude and timing to the perturbation to maintain stability and avoid falls (Chambers & Cham, 2007; Inglis, Horak, Shupert, & Jones-Rycewicz, 1994). A very high or low magnitude of response may indicate impairment in reactive balance control and may predispose an individual to falls. The reactive activation of muscles, swinging of arms, and/or compensatory steps in response to an unexpected slip perturbation during walking has not been studied in individuals with iSCI.

The objective of this study was to use an unexpected slip paradigm to compare reactive responses between individuals with and without iSCI. Specifically, we examined the (a) ability to increase the margin of stability (i.e. distance between center of mass and boundaries of base of support) after a compensatory step; (b) reactive onset of changes in the trajectories of the arms and trail heel; and (c) reactive onset timing and magnitude of lower extremity EMG muscles. We compared the reactive responses in individuals with iSCI to that in age-and sex-matched AB individuals. We hypothesized that individuals with iSCI would have a reduced ability to increase the margin of stability with a compensatory step, a slower onset of changes in limb trajectories, and a delayed onset and a smaller magnitude of reactive muscle activity compared to AB individuals.

4.2 Methods

4.2.1 Participants.

Adults with chronic iSCI (≥ one-year post injury) were recruited through regional health centres and advertisements within the province. Inclusion criteria included individuals with injuries classified as AIS C or D, and the ability to walk 10 m without physical assistance from another person (walking aids and brace(s) permitted). Age- and sex-matched AB individuals were recruited through local advertisements. Exclusion criteria for both groups included any disease or injury that could affect walking or balance ability (e.g. vestibular conditions, joint

pain, etc.), with the exception of SCI for those in the SCI group. The study was approved by the institution's research ethics board.

4.2.2 Experimental procedure.

Participants walked along a 10 m walkway at their self-selected speed wearing comfortable shoes and a safety harness which was attached to a fall prevention system in the ceiling. A set of low friction steel rollers (coefficient of friction = 0.09; 0.46 x 0.51m) were used to provide a slip perturbation. The rollers were placed in the middle of the walkway, flush with the floor surface, and could be unlocked without any visible changes to provide a slip perturbation in the anterior-posterior (AP) direction. No familiarization trials were included to prevent any fatigue in individuals with iSCI. Three to five normal walk (NW) trials were obtained with the slip device locked (i.e., no slip perturbation), following which the slip device was unlocked without the participant knowing for an unexpected slip trial. Following the slip trial, participants were asked if the slip was unexpected or not. Data were not included if the participant indicated they were expecting the slip in order to include only purely unexpected slip responses.

Biomechanical data were collected bilaterally, with the upper and lower extremities on the side that initiated foot contact labelled as the lead extremities, and those on the contralateral side labelled as the trail extremities. Ground reaction force (GRF; fs = 2000 Hz) data were obtained using two force plates (0.46 × 0.51 m, AMTI OR6-7, Advanced Mechanical Technology, Inc., Watertown, MA) embedded in the walkway (one under the slip device and the other diagonally adjacent to the slip device) (Figure 4.1). Surface electromyography data (fs = 2000 Hz) were collected from tibialis anterior (TA), soleus (SOL), and gluteus medius (GM) using a telemetered EMG system (2400GT2, Noraxon Inc, Scottsdale, AZ). Accurate electrode placement was confirmed with voluntary contractions. Kinematic data (fs = 100 Hz) were obtained using an eight-camera 3D motion capture system (Vicon Nexus, Vicon Motion Systems, Centennial, CO). Sixty-three reflective markers (14 mm diameter, 22 calibration) were placed on the participant to capture kinematic data from 12 segments (head, trunk, and right and left upper arms, forearms, thighs, shanks, and feet). Anthropometric data for older (>60 years) (Hanakova et al., 2015; Jensen & Fletcher, 1994; Pearsall, Reid, & Ross, 1994; Yeadon, 1990) and younger (de Leva, 1996) adults according to the age of the participant were used to calculate

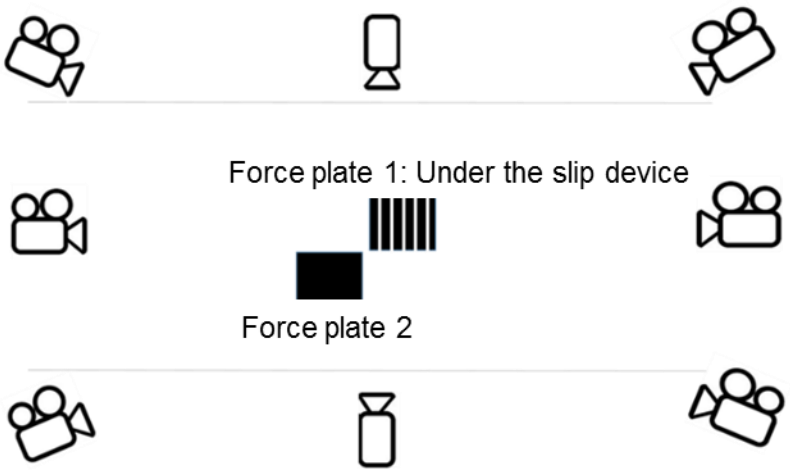
segmental and total body COM . Peak heel marker slip velocity in the AP direction was obtained after the first contact on the slip device for the unexpected slip trial and was used to categorize the slip as hazardous ($\geq$ 1 m/s) or non-hazardous (< 1m/s) (Moyer, Chambers, Redfern, & Cham, 2006). Total body extrapolated COM (XCOM) was calculated based on the position and velocity of COM (Hof, Gazendam, & Sinke, 2005; McAndrew Young & Dingwell, 2012), and was used to calculate the margin of stability by comparing the XCOM position to the posterior (defined by the heel marker of the stance foot during unilateral support or heel marker of the trail foot during double support stance) and lateral (defined by the marker on most lateral aspect of lead foot at the base of fifth metatarsal) edge of the base of support (BOS), respectively. Observation of the reactive step was used to categorize the response as a compensatory step (a premature end of the stance with a step or toe touch down), aborted step (preventing lift-off of the trail limb), or swing through (continuation of the regular swing with change in trajectory) (Bhatt, Wening, & Pai, 2005; Marigold & Patla, 2002).

The 10-meter Walk Test was administered to the individuals with iSCI to measure self-selected (10mWT-SS) and fast (10mWT-Fast) walking speeds (Bohannon, 1997; van Hedel, Wirz, & Dietz, 2005). Participants walked in a 14 m hallway, first at a self-selected speed and then at their fastest, safe speed. Time taken over the middle 10 m was recorded and speed in meters per sec (m/s) was calculated. Scores on a measure of walking capacity – the Walking Index for Spinal Cord Injury II (WISCI II) were also obtained. The WISCI II consists of 21 items that rank walking according to the required amounts of physical assistance, braces, and walking aids (Ditunno Jr et al., 2007).

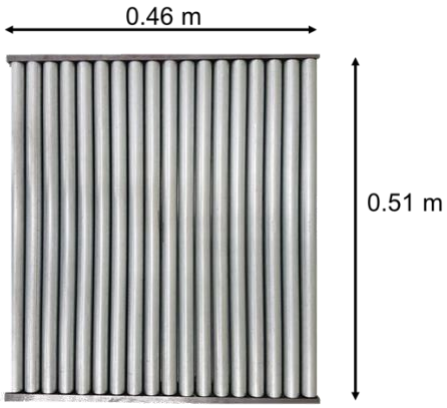
4.2.3 Data analysis.

All kinematic data were low pass filtered at 10 Hz with a 4th order Butterworth filter. EMG data were full-wave rectified and low pass filtered at 6 Hz with a 4th order Butterworth filter. A kinematic data based algorithm was used to detect foot-contact (i.e. the time point when any part of the foot came in contact with the supporting surface) and foot-off (i.e. the time point following foot contact when no part of the foot was in contact with the supporting surface) events (Bruening & Ridge, 2014; Ghoussayni, Stevens, Durham, & Ewins, 2004). This algorithm was based on the resultant velocity signal from the heel and toe. The values obtained from the calculations were adjusted after comparisons with the videos of various individuals to get

consistent detections. Walking velocity of all walking trials was obtained by calculating the average velocity of the COM for each trial and the average of the NW trials was calculated. All kinematic and EMG data were examined over the stance period of each leg (foot-contact to foot-off). Kinematic data were interpolated over a 100-points, whereas EMG data were interpolated over a 1000- points. An average stance time was calculated using all the stance periods from the NW trials. This average NW stance time was also used as the slip stance time when examining the kinematic and EMG data, as slip stance is typically interrupted prematurely with a compensatory step (Tang & Woollacott, 1998).



(a)



(b)

Figure 4.1. (a) Schematic representation of the lab setting for data collection; (b) slip device used to provide slip in the antero-posterior direction when rollers are unlocked

The following variables were extracted to quantify the reactive response: (1) Changes in margin of stability; (2) Onset of arm and trail heel response; (3) Onset of muscle activity

response; and (4) Magnitude of muscle activity response. Reactive changes in the margin of stability were calculated only for those participants who had a compensatory or aborted step. Changes in the lateral (ΔMOS_Lat) and posterior (ΔMOS_Post) MOS values were calculated by subtracting the value at foot-off of the compensatory step from the value at foot contact of the compensatory step of the trail limb (Salot, Patel, & Bhatt, 2016). The ΔMOS_Lat and ΔMOS_Post were normalized to the average NW step width and step length, respectively, as step width is related to lateral MOS and step length is related to posterior MOS (McAndrew Young & Dingwell, 2012). For calculation of the onset of arm and trail heel reactive responses, data from both wrists and the trail limb heel markers were used. Arm and trail heel position trajectories in the AP, ML, and vertical directions for the NW and slip stance durations were obtained. Three-dimensional position vectors were calculated from the summation of the AP, ML, and vertical direction components of the position trajectories. Velocity trajectories were then calculated by taking a first-order derivative of the position trajectories relative to time separately for the slip side arm, trail side arm, and the trail side heel. An average NW stance velocity arm and heel trajectory was obtained by calculating the mean of all velocity trajectories of NW stance periods. Similar to a previous study, reactive onset of arm and trail heel reactive response was the point when the velocity trajectory during the slip stance period went beyond two standard deviations of the average NW stance velocity trajectory in any direction and remained outside for at least 5% (32ms - 61ms) of the slip stance duration (Marigold & Patla, 2002). The reactive onset point was visually confirmed by examining the kinematic data and recorded as both the absolute time (ms) and percentage of the average NW stance time for that participant. A delay in these responses may indicate balance impairments and may predispose individuals to falls (Patla, 2003).

The EMG data for all NW stances were averaged and compared to slip stance data to obtain onset and magnitude of reactive muscle activity. The onset of reactive muscle activity was the point when the slip stance EMG exceeded three standard deviations of the average NW stance EMG in either direction and remained there for at least 5% (32ms - 61 ms) of the total stance time (Marigold & Patla, 2002). Three standard deviations appeared to be sensitive enough and more reliable in detecting reactive EMG onset than two standard deviation for these data. The onset was recorded as the absolute time (Reactive EMG Onset Time) and also relative to the percentage of stance in percent (Reactive EMG Onset Percent). Percentage of stance was used to

identify at what percentage of the gait cycle the onset was experienced. Reactive Integrated EMG (RiEMG) was used as an indicator of the magnitude of the reactive EMG response and was obtained by calculating the difference between the integrated EMG of slip stance from the integrated EMG of the average NW stance. The RiEMG values were divided into three regions: 0-100ms ($Area_{0\text{-}100}$), 100-200ms ($Area_{100\text{-}200}$), and 200-500ms ($Area_{200\text{-}500}$) based on previous literature (Patla, 2003) representing different types of motor control – $Area_{0\text{-}100}$ represents reflexive activity, $Area_{100\text{-}200}$ represents functionally relevant behavioural responses, and $Area_{200\text{-}500}$ represents recovery responses. A higher value of RiEMG in a specific time region indicated a greater amplitude of muscle activation during the reactive slip response.

4.2.4 Statistical analysis.

Normality was tested using a Shapiro-Wilk test. If non-normally distributed, data were transformed using a two-step approach for transforming continuous variables (Templeton, 2011). Height, and mass were compared using a multivariate general linear model between iSCI and AB groups. Average walking velocities were compared using a repeated measure general linear model with NW and Slip conditions as within-subjects and iSCI/AB groups as between-subjects factors. Separate analyses were performed for Δ MOS, onset of arm and trail heel response, reactive EMG Onset, and RiEMG. A multivariate general linear model was used to compare Δ MOS_Lat and Δ MOS_Post between the iSCI and AB groups. Arm trajectory onsets were compared using a repeated-measures general linear model with slip and trail sides as within-subjects factors and iSCI and AB as between-subjects factors. As there were no significant main effects or interactions, an average for the right and left arms was calculated and used. A multivariate general linear model was used to compare arm and heel reactive onset time and percentage between iSCI and AB groups. Onset percent and time of reactive muscle activity were compared using a repeated-measures general linear model with iSCI/AB group as between group factors and slip/trail side as within-subjects factor. Separate analyses were performed for each muscle. A repeated-measure general linear model with iSCI/AB group as between group factors and slip/trail side and three regions of area – $Area_{0\text{-}100}$/$Area_{100\text{-}200}$/$Area_{200\text{-}500}$ as within-subjects factors was used to compare RiEMG.

The assumption of equality of variance for the multivariate analyses was tested using Box's Test. Pillai's Trace values were used with the multivariate analyses if Box's test was not

significant; Wilk's Lambda were used if it was significant. Follow-up repeated measures ANOVA or *t*-tests were used depending on the level of interactions. Alpha was set at 0.05 and Bonferroni corrections were applied during multiple follow-up tests.

4.3 Results

Twenty individuals with iSCI and 15 age- and sex-matched AB individuals participated in the study (Table 4.1). One participant with iSCI stated he was expecting a slip throughout the data collection. His walking velocity for all trials that was slower than the mean velocity of the iSCI group, supporting his claim, and so his data were excluded. Three participants with iSCI did not report expecting the slip trial, but did not slip at all, hence their data and the data from their AB matches were excluded from the analysis.

This left data from 16 participants with iSCI (all AIS D, 8 with tetraplegia, 10 had a traumatic onset, and time since injury = 2.01 years - 16.11 years; median = 5.3 years). Not all individuals with iSCI had age-and-sex matched AB participants, which left 13 AB participants to be included in the study. Participants with iSCI had high walking capacity as indicated by high scores on the WISCI II (median = 20, range = 18-20). Height and mass were not significantly different between the iSCI and AB groups.

Nine participants with iSCI (56%) had a non-hazardous slip, and seven (44%) had a hazardous slip. Four AB participants (31%) experienced a non-hazardous slip, while the remaining nine (69%) had a hazardous slip. During the unexpected slip, 20 participants (12 (75%) iSCI and 8 (62%) AB) took a compensatory step, five (two (12%) iSCI and three (23%) AB) had an aborted step, and four (two (12%) iSCI and two (15%) AB) had a trail limb swing through response. There were no significant between-subjects or within-subjects effects for walking velocity, indicating individuals with iSCI and AB participants walked at similar speeds for both NW and the Slip trials. There was a significant difference in Δ MOS_Lat between groups (F (2, 20) = 4.62, p = 0.022, partial eta squared = 0.316, observed power = 0.71). On follow-up *t*-tests, participants with iSCI were found to have a significantly (t (21) = -2.49, p=0.021) smaller (n=13, M= -0.05, SD=0.24 vs n=10, M = 0.18, SD = 0.18) ΔMOS_Lat values than AB participants (Figure 4.2). The ΔMOS_Post between the iSCI and AB groups were not significant.

Table 4.1
Participant Characteristics

iSCI (n=16)							Able-bodied (n=12)						
ID	**Age (years)**	**Sex**	**Height (m)**	**Mass (kg)**	**NW Velocity (m/s)**	**Slip Trial Velocity (m/s)**	**ID**	**Age (years)**	**Sex**	**Height (m)**	**Mass (kg)**	**NW Velocity (m/s)**	**Slip Trial Velocity (m/s)**
Included Participants													
1	51.42	M	1.92	123.30	0.82	0.86	1	51.63	M	1.88	120.80	0.98	0.91
2	75.98	M	1.68	81.30	0.37	0.34	2	42.21	M	1.86	74.30	0.90	1.03
3	40.58	M	1.80	72.00	0.87	0.89	3	72.76	M	1.64	67.20	1.29	1.33
4	72.94	M	1.71	78.10	0.51	0.45	4	49.10	M	1.86	78.50	0.87	0.78
5	47.43	M	1.67	81.00	0.82	0.75	5	29.20	M	1.73	69.10	1.27	1.00
6	29.77	M	1.75	63.60	1.09	0.99	6	54.80	M	1.76	74.80	0.91	0.84
7	54.72	M	1.72	79.40	0.94	0.88	7	44.75	F	1.71	70.00	1.28	1.30
8	46.35	F	1.61	68.70	0.46	0.63	8	83.63	F	1.57	62.10	0.97	0.78
9	86.34	F	1.56	60.60	0.67	0.72	9	69.41	M	1.75	96.1	0.54	0.62
10	65.68	M	1.81	70.80	0.52	0.53	10	76.71	M	1.84	88.00	0.69	0.70
11	74.21	M	1.78	87.20	0.69	0.65	11	31.88	M	1.79	78.70	1.03	0.88
12	31.97	M	1.89	79.40	1.21	1.16	12	66.80	M	1.72	84.40	1.13	1.08
13	64.81	M	1.73	116.20	0.83	0.92	13	67.10	F	1.64	67.90	0.75	0.92
14	67.86	F	1.62	78.10	1.05	1.16							
15	48.73	M	1.89	96.60	0.89	0.79							
16	40.98	F	1.71	83.10	1.10	0.99							
Mean (SD)	**56.24 (16.77)**	**12M:4F**	**1.74 (0.10)**	**82.46 (17.04)**	**0.80 (0.25)**	**0.79 (0.24)**	**Mean (SD)**	**56.92 (17.24)**	**10M:3F**	**1.75 (0.10)**	**79.38 (15.59)**	**0.97 (0.23)**	**0.96 (0.21)**
Excluded Participants													
17 *	62.58	M	1.78	84.40	0.22	0.20	14	59.90	M	1.83	108.20	1.02	1.16
18 *	45.23	M	1.80	92.30	0.66	0.47	15	94.09	F	1.65	58.8	0.83	0.76
19 *	95.91	F	1.50	60.20	0.24	0.23							
20 #	70.33	M	1.87	131.00	0.30	0.26							

Reasons for exclusion: * did not slip # anticipating slip

Not all participant's data showed an onset of EMG, or change in arm and heel trajectory as per our criteria of selection of onset. The typical change in arm trajectory was in the anterior, superior, and lateral direction for both iSCI and AB groups. The heel moved inferiorly and posteriorly (Figure 4.3). The velocity vectors showed an increase in arm trajectory velocity and a decrease in trail heel velocity for the slip trials as compared to NW trials. There were no significant ($p > 0.05$) differences between iSCI and AB groups in the onset of arm and trail heel reactive responses (Table 4.2). Figure 4.4 shows the typical reactive EMG onset for all muscles. For the TA muscle, there was a significant main effect of group, (F (2, 20) = 3.61, p = 0.046), indicating significantly faster onset of the TA in the AB individuals (Table 4.3). On follow-up independent t-tests, the differences alone in the onset percent or the onset time of reactive TA muscle activity were not found to be significantly different between groups.

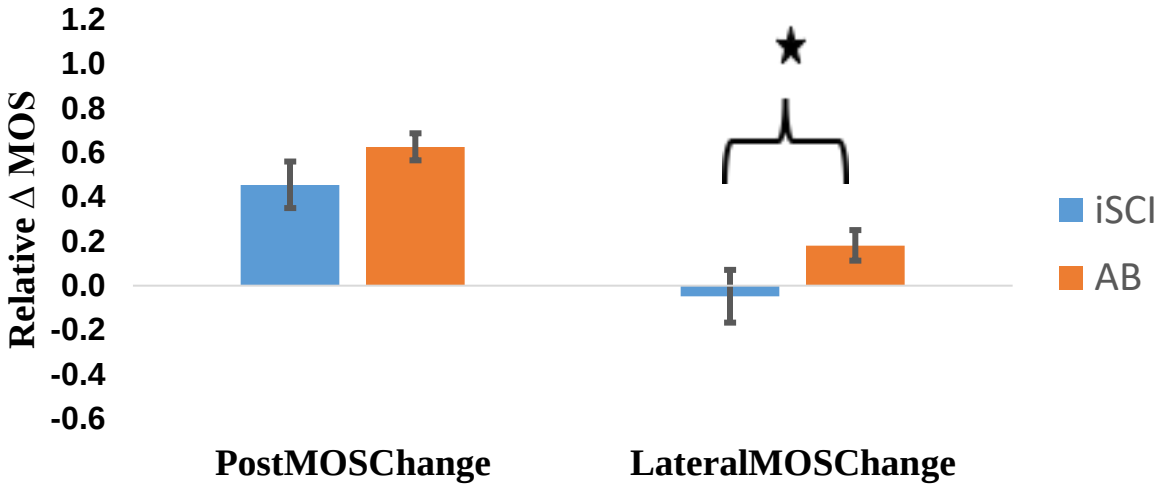


Figure 4.2. Mean and Standard Error of the reactive percentage changes in margin of stability in Posterior and Lateral directions in iSCI and AB groups
* indicates significant differences

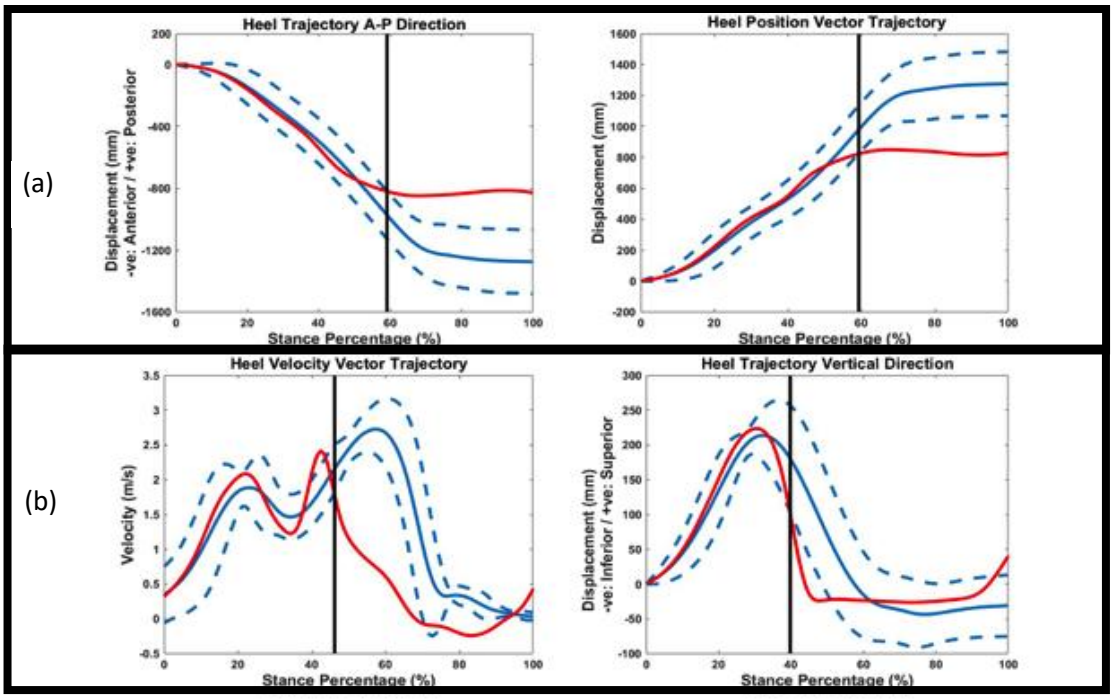


Figure 4.3. Left heel marker trajectories for an individual with iSCI starting from right heel strike (0%) on the slip device to the end of the stance (100%) in (a) position trajectories in AP and vertical directions; (b) combined 3-D position and velocity trajectories.

Mean Normal
Slip
+/- 2 Standard
Reactive Onset

Table 4.2
Average Upper Extremity Reactive Onset Percent and Time with respect to contact on the slip device

	Heel Reactive Onset (Mean ± SD)			Arm Reactive Onset (Mean ± SD)		
	n	Percent (%)	Time (ms)	n	Percent (%)	Time (ms)
iSCI	12	40.00 ± 8.59	376.95 ± 100.52	14	36.97 ± 5.67	345.48 ± 69.98
AB	11	34.38 ± 9.03	301.73 ± 82.01	11	30.88 ± 8.63	281.44 ± 79.20

Reactive Onset: time point when the heel or arm velocity trajectory for the slip stance went beyond two standard deviations of the average NW stance velocity trajectory in any direction and remained outside for at least 5% of the stance
No significant differences between AB and iSCI groups

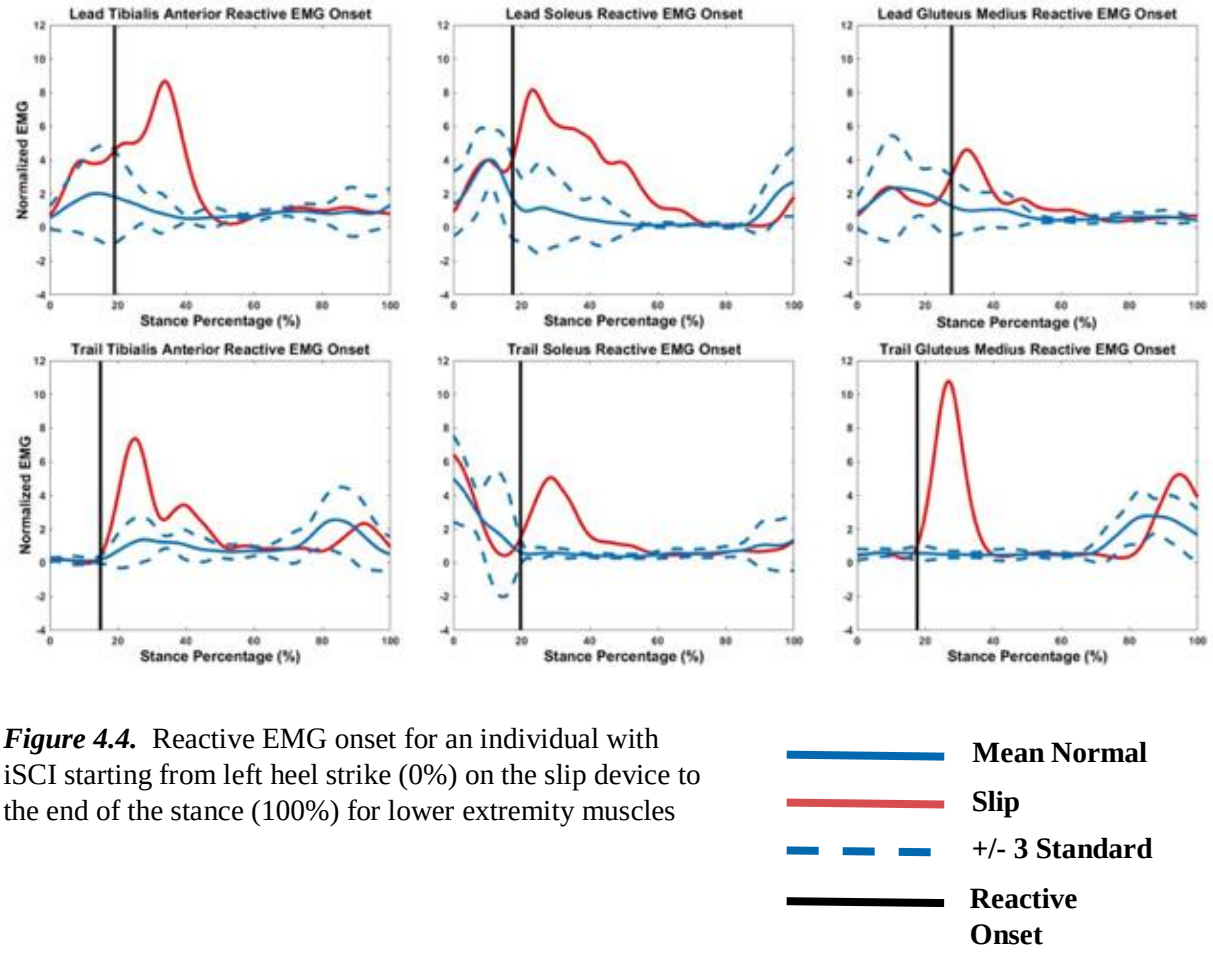


Figure 4.4. Reactive EMG onset for an individual with iSCI starting from left heel strike (0%) on the slip device to the end of the stance (100%) for lower extremity muscles

There were no significant differences between the slip and trail side for the TA onset percent or time (Table 3). For the RiEMG of TA muscle, there was a significant interaction between the slip/trail side and the $Area_{0\text{-}100}$/$Area_{100\text{-}200}$/$Area_{200\text{-}500}$ regions, (F (2, 26) = 3.69, p = 0.039, partial eta squared = 0.221, observed power = 0.63), indicating an overall greater magnitude of activation in the slip side TA as compared to the trail side TA. On follow-up dependent t-tests between slip and trail sides for the three regions, the slip side TA was found to have a significantly greater magnitude of activation than the trail side TA for the $Area_{200\text{-}500}$ region (p = 0.024). There were no significant differences between groups (Table 3). For the SOL muscle activity, there was a significant main effect for slip/trail side for onset percent and time (F (2, 17) = 8.89, p = 0.002, partial eta square = 0.511, observed power = 0.94). On follow-up dependent t-tests, SOL activation was significantly faster both in percentage and time (n=20,

M=23.77%, SD=7.41% or M=215.50ms, SD=78.12ms) on the trail side as compared to the slip side (n=20, M=33.13%, SD=10.59% or M=300.64ms, SD=111.57ms) (Table 3). There were no significant differences between groups for SOL onset percent and time. For the SOL muscle RiEMG, there was a significant interaction between iSCI/AB group, $Area_{0\text{-}100}$/$Area_{100\text{-}200}$/$Area_{200\text{-}500}$ regions, and slip/trail side, (F (26, 2) = 4.53, p = 0.021, partial eta square = 0.258), observed power = 0.72. On follow-up repeated measures ANOVA for individual area regions, a significant interaction was noted between iSCI/AB group and slip/trail side only for the $Area_{200\text{-}500}$, (F (1, 27) = 8.15, p = 0.008, partial eta square = 0.232, observed power = 0.85). On follow-up paired t-tests for the $Area_{200\text{-}500}$ region, there was a significantly greater activity on the trail side as compared to the slip side in both iSCI (p = 0.013) and AB participants (p < 0.001). On independent t-tests, AB participants were found to have a significantly (p = 0.006) greater magnitude of trail side SOL activity than participants with iSCI for the $Area_{200\text{-}500}$ region (Table 3).

For the GM muscle, there was a significant main effect for slip/trail side for onset percent and time (F (2, 18) = 8.80, p = 0.002, partial eta square = 0.494, and observed power = 0.94; Table 3). On follow-up paired t-tests, GM muscle activation was significantly (p = 0.001) faster in percentage and time (n=21, M=22.13%, SD=10.29% or M=195.23ms, SD=86.72 ms) on the trail side as compared to the slip side (n=21, M=31.47, SD=9.10% or M=280.94, SD=85.76 ms). For GM muscle RiEMG**,** there were no significant main effects or interactions; however, the interaction between slip/trail side and $Area_{0\text{-}100}$/$Area_{100\text{-}200}$/$Area_{200\text{-}500}$ regions was approaching significance (F (2, 26) = 3.23, p = 0.056, partial eta square = 0.199, observed power = 0.56). Comparing the mean onset scores of different muscles, on the slip side, the TA muscle was activated the fastest and the SOL muscle was the last to be activated in individuals with iSCI and AB individuals. On the trail side, a similar pattern to the slip side was seen in AB participants; however, iSCI group activated their GM muscle first and TA muscle last.

Table 4.3
Mean ± SD for EMG onsets and REMG

Variable	Group		Slip Side			Trail Side		
			TA	SOL	GM	TA	SOL	GM
EMG Onset, % (time)	iSCI	**% ± SD**	**25.17 ± 11.21**	**34.03 ± 11.24**	31.56 ± 8.71	24.90 ± 9.65	**23.25 ± 7.81**	20.33 ± 11.01
		Time±SD (ms)	**241.66 ± 100.57***	**317.00 ± 133.35**	291.81 ± 91.60	243.55 ± 107.98	**215.65 ± 93.55**	187.94 ± 104.98
		N	**12**	**10**	11	12	**10**	11
	AB	**%± SD**	**23.70 ± 5.71**	**32.24 ± 10.43**	31.38 ± 9.99	20.73 ± 5.63	**24.29 ± 7.37**	24.10 ± 9.60
		Time±SD (ms)	**198.94 ± 50.12***	**284.28 ± 88.90**	268.99 ± 81.95	171.44 ± 44.48	**215.35 ± 64.30**	203.25 ± 65.80
		N	**11,**	**10**	10	11	**10**	10
RiEMG $Area_{0-100}$	iSCI (N=16)		66.78 ± 119.69	-3.77 ± 42.42	3.48 ± 45.21	40.96 ± 69.00	-11.46 ± 104.30	-1.38 ± 21.24
	AB (N=13)		-51.22 ± 92.35	4.52 ± 27.37	-12.90 ± 84.97	-8.35 ± 6.05	-56.33 ± 82.41	-14.84 ± 52.61
RiEMG $Area_{100-200}$	iSCI (N=16)		136.78 ± 193.93	6.58 ± 54.60	-3.93 ± 60.89	96.18 ± 99.21	3.00 ± 75.36	35.08 ± 54.05
	AB (N=13)		77.82 ± 210.06	8.59 ± 36.86	-6.10 ± 95.28	68.46 ± 69.14	39.60 ± 157.00	66.68 ± 240.51
RiEMG $Area_{200-500}$	iSCI (N=16)		**806.71 ± 464.61**	**142.61 ± 386.63**	595.94 ± 747.86	**659.64 ± 785.48**	**583.91 ± 569.53***	824.44 ± 636.37
	AB (N=13)		**1294.88 ± 827.98**	**302.85 ± 352.13**	1086.94 ± 1117.14	**643.08 ± 476.87**	**1604.16 ± 1062.93***	1189.26 ± 896.65

All significant differences are bolded; Shaded: significantly different between Slip/Trail limb; *: significantly different between iSCI/AB group

4.4 Discussion

This study investigated the reactive balance responses in response to an unexpected slip perturbation in individuals with iSCI. Specifically, the study looked at the ability to change the margin of stability using a compensatory step response, activate lower extremity muscles, and change arm and trail heel velocity trajectories in response to an unexpected slip. It was hypothesized that individuals with iSCI would have a reduced ability to increase the margin of stability with a compensatory step, have a delayed onset and a smaller magnitude of reactive muscle activity, and a slower onset of changes in limb trajectories compared to AB individuals. Our hypothesis was partially supported by a significantly smaller increase in the margin of stability in the lateral direction in individuals who took a compensatory step, slower onset of TA EMG activity, and a smaller magnitude of EMG activation in the trail side SOL muscle between 200-500 ms post slip in individuals with iSCI as compared to AB individuals. The other responses, such as ΔMOS_Post, onset of arm and trail heel response, and reactive EMG onset and RiEMG of other muscle groups were similar between iSCI and AB groups, which could have been due to high functioning levels (AIS D, median WISCI II = 20) of participants with iSCI.

4.4.1 Change in dynamic margin of stability.

We used ΔMOS to capture the ability to regain stability after a perturbation. Conceptually, this measure evaluates the control of the COM/BOS relationship during a compensatory step. Previous research has found a limited ability in individuals with chronic stroke to regain stability using a compensatory step after an unexpected slip in the posterior direction (Salot et al., 2016). In our study, individuals with iSCI were able to increase their margin of stability in the posterior direction similar to AB individuals; however, in the lateral direction, individuals with iSCI had a limited ability compared to AB individuals. The differences between this and previous studies could be due to the differences in the populations and the methods of perturbations used: In addition to the previous study examining individuals who have had a stroke (Salot et al., 2016), it also used a motorized treadmill for the perturbation which is different from a slip induced with a low-friction surface. Surface translation provides more control for the researcher over the magnitude of perturbation but there is no displacement of the foot relative to the surface. Results of our study confirm limitations in ability of

individuals with iSCI to regain COM/BOS relationship during a compensatory step following unexpected perturbation, which indicate limitations in their reactive balance control.

4.4.2 EMG onset pattern and timing and locus of control – slip side vs trail side EMG.

A rapid onset of reactive response in the lower extremity muscles was observed in all participants. Although there is no clear agreement on the pattern of lower extremity muscle activation, most studies have reported fastest activation of the TA on the lead side (Chambers & Cham, 2007; Marigold & Patla, 2002; Tang & Woollacott, 1998), which is similar to what we found in our study for both iSCI and AB groups. Both groups also showed slower activation of SOL muscle in the lead lower extremity than the lead TA and GM muscles. On the trail side, a difference in activation pattern was observed between iSCI and AB groups, with the iSCI group activating the GM muscle first and TA muscle last. In contrast, the AB group activated the TA muscle first and the SOL muscle last. The differences between the lead and the trail sides can be due to the differences in the responsibilities of the slip and trail sides, with the trail side more involved in initiating stepping and weight bearing (Marigold, Bethune, & Patla, 2002; Pai & Bhatt, 2007). Previous research suggests the trailing limb plays an important role in balance control after a slip perturbation as indicated by a comparable or even faster EMG onset of the trail limb muscles as compared to the slipping limb (Marigold et al., 2002; O'Connell, Chambers, Mahboobin, & Cham, 2016). In our study, there was a significantly faster onset of SOL muscle on the trail side as compared to the lead side, irrespective of group. The differences were also observed in the magnitude of muscle activation mainly between 200-500 ms, which is the region for voluntary reactive responses (Patla, 2003). For both groups, a greater activation of the TA muscle was seen on the slip side, whereas a greater activation of SOL muscle was seen on the trail side. The TA muscle activation on the slip side has been shown to be important for slip recovery in healthy young and older adults (Chambers & Cham, 2007). A greater activation of SOL on the trail side may be indicative of a preparation for weight bearing. Individuals with iSCI were not able to generate as much activation in the trail side soleus muscle in the $Area_{200\text{-}500}$ region as compared to that generated by AB individuals, indicating a limitation in voluntary activation of the SOL muscle following an unexpected slip.

Older individuals tend to have slower onset and smaller magnitude of activation of lower extremity muscles in response to an unexpected slip as compared to younger individuals (Tang & Woollacott, 1998). A slower onset can be compensated by a stronger response; however, a combination of slow muscle onset and a smaller magnitude of muscle activation indicates ineffective reactive balance control (Tang & Woollacott, 1998). Individuals with iSCI demonstrated both a slower onset of TA activation, and smaller magnitude of SOL muscle activation indicating limitations in their reactive balance control following an unexpected slip perturbation.

4.4.3 Reactive change in trajectory.

A typical response to the slip in all participants was elevating the arms forward and laterally. Similar reactive arm responses have been reported previously in AB (Marigold & Patla, 2002) and older adults (Tang & Woollacott, 1998). Raising the height of arms in any direction helps to prevent lowering of the COM resulting from the slip, while forward movement of the arms helps to counteract the backward movement of the COM. Forward and upward movement of arms are important to control the COM position to prevent the backward loss of balance from the slip (Marigold & Patla, 2002). No iSCI/AB group differences were observed in reactive arm or heel trajectory onset time or percentages indicating both groups were able to move their limbs equally fast.

4.4.4 Limitations.

The limited size of the slip device, and providing a perturbation under only one foot could have limited the extent of the slip; however, the peak velocity of the slip achieved was comparable to that reported in a previous study (Cham & Redfern, 2002). The participants with iSCI had an AIS D impairment level, which prevents the generalizability of results to individuals with lower functioning levels (AIS C).

4.5 Conclusion

This study examined the reactive responses of individuals with iSCI and AB individuals using an unexpected slip perturbation during walking. Like AB individuals, individuals with iSCI demonstrated a greater magnitude of TA activation on the slip side and SOL activation on the trail side. The onset of changes in arm and trail heel trajectory were similar in individuals with iSCI and AB individuals. The ability to regain stability in the antero-posterior direction was

also comparable between the two groups. Unlike AB individuals, individuals with iSCI demonstrated a limited ability to increase the margin of stability in the lateral direction during a compensatory step. Individuals with iSCI also had a slower onset of TA and a smaller magnitude of reactive SOL activity as compared to AB individuals. These results suggest there are limitations in the reactive balance control of individuals with iSCI; therefore, it is important to include reactive balance control in the assessment of individuals with iSCI and to further investigate efforts to improve reactive balance control in this community.

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RELEVANCE OF CHAPTER FOUR TO THE THESIS

Reactive responses, following an unexpected perturbation are important to maintain stability and avoid falls (Chambers & Cham, 2007; Patla, 2003). This study assessed the reactive balance responses to an unexpected slip perturbation in individuals with iSCI. Individuals with iSCI demonstrated a limited ability to regain lateral stability with a compensatory step, a slower onset of tibialis anterior (TA) muscle activity, and a smaller magnitude of reactive SOL activity as compared to AB individuals. These findings confirm there are limitations in the reactive responses to an unexpected slip perturbation in individuals with iSCI. These results, combined with the results of our previous study about walking stability (Chapter 3), support the idea that individuals with iSCI adopt proactive strategies during normal walking to compensate for the limitations in their ability to generate reactive responses. The importance of assessing the reactive component during balance assessment is highlighted again in this study.

CHAPTER FIVE: CURRENT STATE OF BALANCE ASSESSMENT FOR THE SCI POPULATION: A SYSTEMATIC REVIEW

5.1 Introduction

Over 280,000 Americans are living with a spinal cord injury (SCI) (National Spinal Cord Injury Statistical Center, 2016). The injury can cause sensorimotor deficits that frequently manifest as impaired balance, which in turn can lead to falls. The rate of falls for individuals with SCI who are ambulatory (75% in one year (Brotherton, Krause, & Nietert, 2007)) is higher than those individuals with SCI who use a wheelchair (33% in one year (Nelson et al., 2010)). Wheelchair-users typically fall during transfers (Nelson et al., 2003), whereas ambulatory individuals fall while performing an upright activity like walking (Amatachaya, Wannapakhe, Arrayawichanon, Siritarathiwat, & Wattanapun, 2011). Falls can lead to injuries (Jorgensen, Butler Forslund, et al., 2017), costly hospital admissions (Dryden et al., 2004), a fear of falling, and subsequent restriction in community participation (Musselman, Arnold, Pujol, Lynd, & Oosman, 2016).

Balance or postural control involves maintaining, achieving, or restoring a state of stability during any posture or activity (Pollock, Durward, Rowe, & Paul, 2000). Effective balance control is essential for avoiding falls and is dependent on the integration of various sensory inputs, and the interaction of the body with the changing environment (Sibley, Beauchamp, Van Ooteghem, Straus, & Jaglal, 2015). A modified version of the Systems Framework for Postural Control (Horak, 2006; Sibley et al., 2015) identifies nine major components for the maintenance of balance – 1) functional stability limits (e.g. size of base of support (BOS) (Lemay & Nadeau, 2013)), 2) underlying motor systems (e.g. muscle strength), 3) static stability (e.g. maintaining center of mass (COM) within BOS (Lemay & Nadeau, 2013)), 4) verticality (e.g. orienting the body parts relative to gravity, the support surface, visual surround, and internal references (Bisdorff, Wolsley, Anastasopoulos, Bronstein, & Gresty, 1996)), 5) reactive postural control (e.g. hip or ankle movement to regain body equilibrium after balance is perturbed (Thigpen et al., 2009)), 6) anticipatory postural control (e.g. modulation of lower extremity muscle activity in anticipation of a perturbation (Thigpen et al., 2009)), 7) dynamic stability (e.g. maintaining body equilibrium in situations when the BOS is changing

(Lemay, Duclos, Nadeau, Gagnon, & Desrosiers, 2014)), 8) sensory integration (e.g. re-weighting the contributions of somatosensory, visual and vestibular inputs depending on the context and sensory capabilities of the individual (Lemay & Nadeau, 2013; Peterka, 2002)), and 9) cognitive influences (e.g. how attentional resources are allocated to maintain balance while performing a task (Teasdale & Simoneau, 2001)). The postural strategies selected by individuals are context-specific and depend on functional abilities, environmental conditions, and the task demands (Horak, 2006). Acknowledging the different components of postural control is important for the assessment of balance, the identification of individuals at increased risk of falls, the design of effective fall prevention programs, and the monitoring of changes in balance control over time. A comprehensive balance assessment measure should capture all components of balance (Horak, 2006).

Compared with older adults and other neurological populations (Noohu, Dey, & Hussain, 2014; Tyson & Connell, 2009; Whitney, Poole, & Cass, 1998), there is a paucity of information regarding what measures of balance are available and appropriate for the SCI population (Kahn et al., 2016). The SCI EDGE Task Force recently published recommendations concerning outcome measurement in SCI rehabilitation practice and teaching (Kahn et al., 2016). Through a consensus-based approach and non-systematic literature searching, the Task Force identified seven measures of balance for the SCI population with one, the Berg Balance Scale (BBS), receiving 'recommended' ratings (Kahn et al., 2016). The recommendation was based on the clinical utility and psychometric properties of the outcome measures, but did not consider comprehensiveness; an important consideration for any measure of balance. Further, given that >50 measures have been validated for the assessment of standing balance in clinical environments in adult populations (Sibley et al., 2015), it is likely that a greater number of balance measures have been used with the SCI population, and would be identified through systematic searching.

This systematic review was designed to provide guidance to clinicians and researchers regarding what balance measures are comprehensive, psychometrically-sound and clinically feasible for individuals with SCI. The objectives were threefold: 1) identify what balance control measures have been used to assess balance during transfers, sitting, standing, and walking in individuals with SCI; 2) evaluate the comprehensiveness (i.e. extent to which

measures are inclusive of the components of the Systems Framework for Postural Control) and psychometric properties of the identified measures; and 3) provide recommendations for the assessment of balance control in individuals with SCI in clinical settings.

5.2 Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were used to conduct a systematic review (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). There is no registered protocol for this review. A research question was formulated systematically by using a modified patient population, intervention or indicator, comparator, outcome, and study design (PICO) framework (Santos, Pimenta, & Nobre, 2007). The population was adults with SCI. The indicator was any measure of balance during sitting, standing, walking, or transferring. There was no comparator. The outcome was balance control or ability to maintain balance. There were no restrictions on the study design with the exception of systematic reviews and meta-analyses.

5.2.1 Search strategy.

Medline, PubMed, Embase, Scopus, Web of Science, and the Allied and Complementary Medicine Database were searched from the earliest record to October 19, 2016 (appendix A) using keywords and controlled vocabulary (as appropriate). Articles were not restricted on the basis of language, date, or type of publication. The reference lists of the articles that were included were screened to identify any relevant studies not returned in the systematic search of the databases.

Abstracts were de-duplicated using a research management tool (RefWorks-COS), and then reviewed independently by two researchers to identify those to be included for full-text screening. The inclusion criteria for full-text screening were as follows: (a) article included a measure of balance, and (b) article included participants with a SCI that were rated an A, B, C or D on the American Spinal Injury Association Impairment Scale (AIS). The acute, sub-acute and chronic stages of SCI were included, as were traumatic and non-traumatic causes of SCI. The exclusion criteria for full-text screening were as follows: (a) article included a measure of mobility, and not balance per se (such as 10-Meter Walk Test, 6-Minute Walk Test, Timed Up-and-Go), (b) conference abstracts, (c) review articles not presenting original data, and (d) animal

studies. In the case of a disagreement regarding inclusion, a third researcher reviewed the abstract to make a final decision. Screening of full-texts for inclusion was divided between all four researchers, with one researcher (TA) reviewing all full-texts to ensure consistency. The same inclusion and exclusion criteria used for the abstract screening were used for the screening of full-texts.

5.2.2 Data extraction.

Data from included full-text articles were entered into a data extraction table. Extracted data included information on participant characteristics, study design, and descriptions of the balance measures used including psychometric properties (explicitly tested validity, reliability and responsiveness). In the case of full-texts written in a language other than English, individuals proficient in that language assisted with data extraction.

Methodological quality was evaluated by adapting the methods of Bisaro et al. (Bisaro, Bidonde, Kane, Bergsma, & Musselman, 2015) and Dobson et al. (Dobson, Morris, Baker, & Graham, 2007). Articles were evaluated on the adequacy of the description of the following: research participants, inclusion/exclusion criteria, sampling methods, method of data collection (i.e. prospective/retrospective), and psychometric properties of the balance measures used in the study. These categories were rated as adequate/partial, stated/not stated or yes/no, depending on the question (see Table 1).

5.2.3 Data synthesis.

The extracted data were synthesized to describe the use of balance measures in individuals with SCI. First, the total number of studies in which each measure was used was counted to identify the most frequently used measures. As the number and variety of measures directly assessing a biomechanical construct were large, these measures were grouped into the following categories to facilitate description: (a) measures related to center of pressure (COP) or COM, (b) electromyography (EMG), (c) forces or torques, (d) joint angles using motion capture, (e) instrumented reaching distance, (f) instrumented gait variables (e.g., foot placement variability), (g) reaction time or movement time, (h) others including fall threshold based on peak velocity and size of excursion, damping factor, and linear momentum.

Table 5.1
Study quality evaluation tool (Adapted from Bisaro et al. (2015) and Dobson et al. (2007)

Question	Decision Rules
Are participants characteristics adequately defined, including age, sex, level of injury, AIS level, time since injury?	- Adequate = all details - Partial = 1 or 2 missing - Inadequate = more than 2 missing
Are inclusion/exclusion criteria stated?	- Stated = Clear list of both - Limited = 1 or 2 points only - Not Stated = no details of either
What was the sampling method used?	- Convenience* - Community-based ǂ - Population-based‡ - Not stated
Was the balance assessment performed prospectively or retrospectively?	- Prospective = balance assessed at the time of study - Retrospective = balance assessed before beginning of the study, e.g. chart review
Was the reliability of the measure stated or demonstrated?	- Yes (list type[s], e.g. inter-rater, test-retest, internal consistency) - No
Was the validity of the measure stated or demonstrated?	- Yes (list type[s], e.g. concurrent, criterion, and content) - No
Was the responsiveness of the measure stated or demonstrated?	- Yes - No

*Participants included patients from the local hospital; ǂParticipants recruited from ≥1 local hospital or organization with the aim of reaching all potential participants in the area; ‡As per community-based, but geographical area larger (e.g., country- or state/province-wide)

Next, the task(s) performed during each balance measure/grouping was identified to provide further description. Categories of tasks included sitting (e.g. supported/unsupported quiet sitting, reaching), standing (e.g. with eyes opened/closed, on stable/unstable surfaces, reaching), walking (e.g. with head turning, changing speed, tandem walk), and transferring (e.g. changing postures as during sit-to-stand or lateral transfers with or without arm use).

The clinical utility of the balance measures was evaluated according to Tyson and Connell (Tyson & Connell, 2009) on the basis of (a) tool administration, analyses, and interpretation time (3: <10minutes; 2: 10-30minutes; 1: 30-60minutes; 0: >1hour), (b) associated cost (3: <£100; 2: £100-£500; 1: £500-£1000, 0: >£1000 or unknown), (c) need of specialized equipment and training (2: no; 1:yes, but simple and clinically feasible; 0: yes, and not clinically feasible), and (d) ease of portability (2: easily; 1: portable in a briefcase or trolley; 0: no or very difficult). According to Tyson and Connell (2009), a score of $\geq$9/10 suggested a balance measure could be recommended for clinical use (i.e. high clinical utility). As balance consists of many components (Sibley et al., 2015), and may be evaluated during different tasks (e.g. sitting, standing, walking, transferring), one would expect some clinically useful measures to take more than ten minutes to complete. Hence, we have lowered the cut-off score to 8; measures scoring 8/10 or greater had high clinical utility.

For measures with high clinical utility, the following information was synthesized: (a) the psychometric properties (i.e. validity, reliability, and responsiveness) established in the SCI population, and (b) the comprehensiveness of each measure. Comprehensiveness was evaluated using the nine operational definitions of balance (Sibley et al., 2015) that were adapted from the original six domains of the Systems Framework for Postural Control (Horak, 2006). If the balance components of a measure were previously identified by Sibley et al. (Sibley et al., 2015), those identified components were reported here. For measures not assessed by Sibley et al. (Sibley et al., 2015), comprehensiveness was evaluated independently by two researchers (TA with AO) with a third researcher resolving any discrepancies (KM).

5.3 Results

A total of 2820 abstracts were obtained after de-duplication, and 222 were retained for full-text screening (Figure 2.1). Following full-text review, 127 articles were included. One of the articles was written in Korean (Kim, Chung, & Shin, 2010) for which data extraction was completed with the help of a person proficient in Korean. The supplementary tables S1 and S2 summarize the data extracted from each study. Participants in these studies had a wide range of characteristics in terms of neurological level of injury (C1 to L5), time since injury (0.1 – 48 years), and age (15.0 – 85.7 years). Forty-two percent of included studies (n = 54) involved individuals with motor incomplete injuries (i.e. AIS C and D), 29% of studies (n = 36) included

motor complete injuries (i.e. AIS A and B), and 22% of studies (n=28) included both motor incomplete and motor complete injuries. The remaining 7% of studies (n=9) did not specify completeness level of the participants. The majority of studies included individuals with SCI solely, whereas 6% of studies (n=7) also included other populations, such as traumatic brain injury (Betker, Desai, Nett, Kapadia, & Szturm, 2007; Freivogel, Mehrholz, Husak-Sotomayor, & Schmalohr, 2008), labyrinthine loss (Tokita, Miyata, Matsuoka, Taguchi, & Shimada, 1976), stroke (Kubota et al., 2013), Parkinson's disease (Fritz et al., 2011), amputation (Pernot et al., 2011), and polio (Altmann et al., 2016).

5.3.1 Quality of studies.

The majority of studies (n=124, 98%) collected data prospectively; only one study reported data from a retrospective chart review (Chan et al., 2017). Two studies (Tamburella, Scivoletto, Iosa, & Molinari, 2014; Tamburella, Scivoletto, & Molinari, 2013; Wirz, Muller, & Bastiaenen, 2010) used a mix of prospective and retrospective data collections (i.e., asking participants about falls experienced in the past was considered a retrospective collection (Wirz et al., 2010)). More than half of the studies (n=74, 58%) provided adequate information on participant characteristics including age, sex, level of injury, AIS level, and time since injury, whereas six (5%) studies did not provide sufficient information (>2 missing items), and 47 (37%) studies provided partial (1-2 missing items) information. With respect to inclusion criteria, 72 (57%) studies stated detailed inclusion criteria, whereas 30 (23%) studies provided only one to two criteria. Twenty-five (20%) studies did not state any inclusion criteria. Few studies used population- or community- based samples (one and six, respectively), with the majority (n=69, 54%) of studies recruiting participants according to convenience. Forty percent (n=51) of the included studies did not report the recruitment strategy used. Thirteen percent (n=17) reported the validity, reliability, or responsiveness of the measures being used in the study. The supplementary table S3 summarizes the quality evaluation for each study.

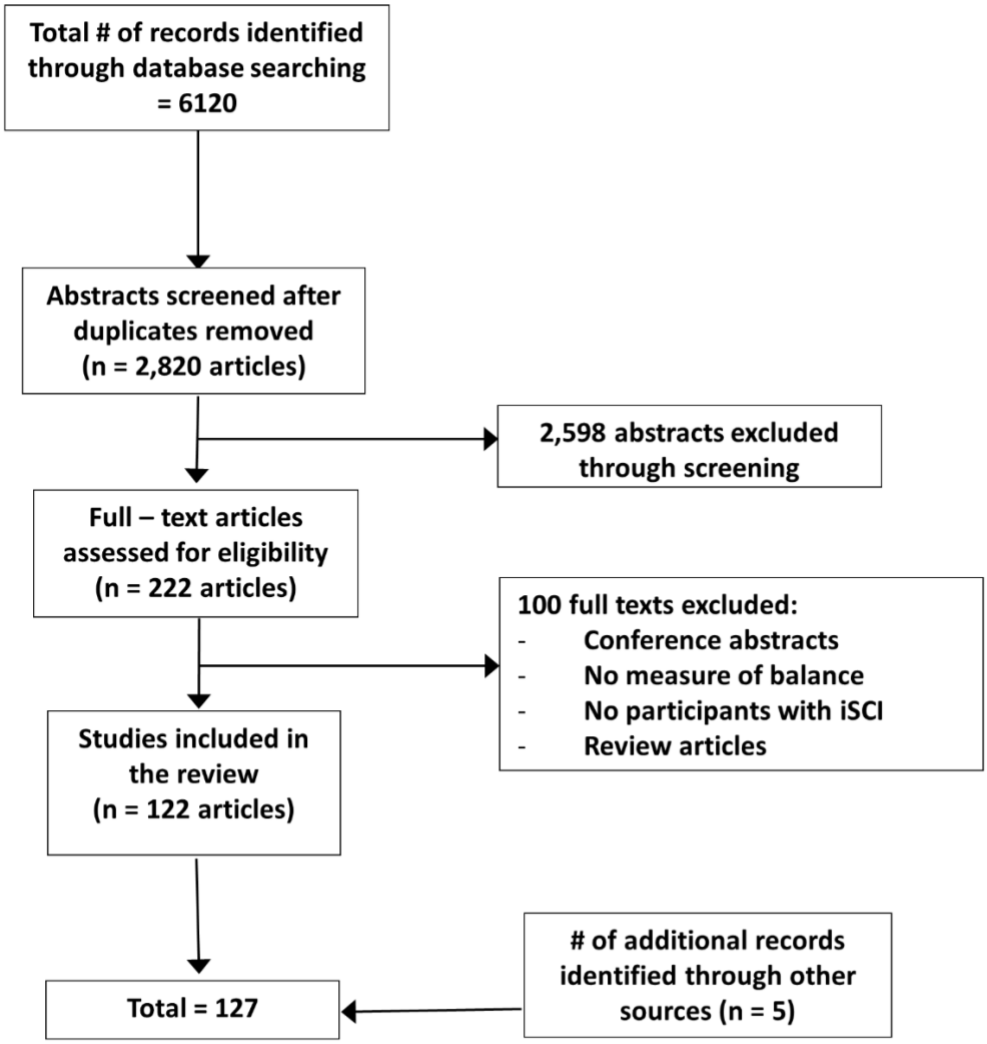

Figure 5.1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram.

5.3.2 Balance measures used with individuals with SCI.

A total of 30 balance measures were identified in this review. Eleven of these measures evaluated a biomechanical construct; for example, COP or COM related measures (Lemay & Nadeau, 2013; Tamburella et al., 2014) and instrumented gait variables (Day, Kautz, Wu, Suter, & Behrman, 2012) (Table 5.2). There was considerable heterogeneity in how the biomechanical constructs were measured; however, all measures fit into one of the groupings listed in Table 5.2.

The most commonly used biomechanical grouping was COP or COM (n=59, 46%), followed by EMG (n=12, 9%) and forces or torques (n=9, 7%). Measures of COP or COM were used to assess balance during all four tasks – sitting (Chaffin, Woolley, Dickerson, & Parkinson, 2004; Gauthier et al., 2012; Karatas, Tosun, & Kanath, 2008; Shin & Sosnoff, 2013), standing (Lemay & Nadeau, 2013; Middleton, Sinclair, Smith, & Davis, 1999), walking (Day et al., 2012) and transfers (Bahrami, Riener, Jabedar-Maralani, & Schmidt, 2000). EMG was utilized to evaluate muscle activity during sitting (Bahrami et al., 2000; Bjerkefors, Carpenter, Cresswell, & Thorstensson, 2009; Janssen-Potten, Seelen, Drukker, Huson, & Drost, 2001) and standing (Liechti, Muller, Lam, & Curt, 2008; Thigpen et al., 2009). Direct (e.g., ground reaction forces and torques) and indirect (e.g., stabilization and destabilization forces) measures of forces or torques were used to assess balance during sitting (Altmann et al., 2016; Triolo, Bailey, Miller, Lombardo, & Audu, 1766; Triolo RJ. Boggs L. Miller ME. Nemunaitis G. Nagy J. Nogan Bailey, 2009), walking (Desrosiers, Nadeau, & Duclos, 2015; Lemay et al., 2014; Lemay, Duclos, Nadeau, & Gagnon, 2015), and transfers (Gagnon, Duclos, Desjardins, Nadeau, & Danakas, 2012).

Some biomechanical groupings captured balance during a single activity: Instrumented reaching distance (de Abreu, Takara, Metring, Reis, & Cliquet Jr, 2012; Field-Fote & Ray, 2010), reaction/movement time (Janssen-Potten, Seelen, Drukker, Spaans, & Drost, 2002; Seelen, Janssen-Potten, & Adam, 2001), damping factor (Bernard, Peruchon, Micallef, Hertog, & Rabischong, 1994), and trunk stiffness (Audu & Triolo, 2015) were utilized to assess balance during sitting, and mainly in individuals with motor complete injuries. Instrumented gait variables and linear momentum were utilized to capture balance during walking (Day et al., 2012; Tamburella et al., 2013; Wu, Landry, Schmit, Hornby, & Yen, 2012) and transfers (Bahrami et al., 2000), respectively. Walking balance was assessed only in individuals with AIS D classification. Nineteen balance measures identified in the review were balance scales, many of which were intended for use in clinical environments. Some balance scales assessed balance during a single activity (e.g. Functional Reach Test (FRT), Romberg sign, Dynamic Gait Index (DGI)), whereas other balance scales included more than one task (e.g. BBS, mini-Balance Evaluation Systems Test (mini-BESTest)) (Table 5.2).

Table 5.2

Clinical utility and tasks evaluated by balance measures

Balance Measure	Number of studies	Clinical Utility Score (/10)	Tasks Evaluated
Groupings By Biomechanical Construct			
a) COP/COM	59	0	(S_i, S_a, W, T)
b) EMG	12	1	(S_i, S_a)
c) Forces/Torques	9	2	(S_i, W, T)
d) Joint Angles using motion capture	7	0	(S_i, S_a)
e) Instrumented Reaching Distance	5	0	(S_i)
f) Instrumented Gait Variables	3	0	(W)
g) Reaction/Movement Times	4	0	(S_i)
h) *Others (4)	4	0	(S_i, S_a, T)
Balance Scales			
a) Berg Balance Scale	43	8	(S_i, S_a, T)
b) Functional Reach Test	21	10	(S_i, S_a)
c) Dynamic Gait Index	3	8	(W)
d) Tinetti Scale	2	9	(S_i, S_a, W, T)
e) Mini-BESTest	1	8	(S_a, W, T)
f) Activity Based Level Evaluation	1	8	(S_i, S_a, W, T)
g) Clinical Test of Sensory Organization and Balance	1	9	(S_i)
h) Test Table Test	1	10	(S_i)
i) Motor Assessment Scale	1	10	(S_i)
j) Sitting Balance Score	1	10	(S_i)
k) Romberg Test	1	10	(S_a, W)
l) Community Balance and Mobility	1	8	(S_a, W)
m) Balance CAT	1	10	(S_i, S_a, T)
n) Body Sway using Sway Meter	1	8	(S_i, S_a)
o) Standardized Obstacle Clearing Tests	2	9	(W)
p) T-shirt test	3	10	(S_i)
q) Timed Standing	1	10	(S_a)
r) Timed Tandem Stance	1	10	(S_a)
s) Seated Reaction to Perturbation	1	10	(S_i)

S_i=sitting; S_a=standing; W=walking; T=transfers; *Others include Damping Factor, Linear Momentum, Trunk Stiffness, Fall Threshold.

The most commonly used balance scale was the BBS (n=43, 34%), followed by the FRT (n=21, 17%), performed in sitting (n=18, 14%), standing (n=2, 2%) or both sitting and standing (n=1, 1%). The remaining balance scales identified were used infrequently (i.e. in ≤3 studies) with individuals with SCI (see Table 5.2).

Twelve balance scales evaluated sitting balance. Eight of these assessed the task of sitting alone (i.e. seated FRT, Test Table Test, Motor Assessment Scale, Sitting Balance Score, Sway Meter, Clinical Test of Sensory Organization and Balance, T-shirt Test, and Seated Reaction to Perturbation), with the seated FRT most commonly used (n=19, 15%). The seated FRT was used to assess sitting balance in individuals with motor complete injuries, with the exception of two studies (Srisim, Saengsuwan, & Amatachaya, 2015; Wall, Feinn, Chui, & Cheng, 2015) that included individuals with motor incomplete injuries. Four scales (BBS, Activity-Based Balance Level Evaluation (ABLE), Tinetti, and Balance CAT) assessed sitting balance along with balance during other tasks and were used with individuals with complete and incomplete injuries. Similarly, 11 balance scales evaluated standing balance in SCI; five scales examined standing balance in isolation (standing FRT, Traditional Romberg, Sway Meter, Timed Standing and Timed Tandem Stance) and six examined standing along with other tasks (BBS, ABLE, Tinetti, mini-BESTest, Community Balance & Mobility Scale (CB&M), and Balance CAT). All of these scales were used in individuals with incomplete injuries, except the BBS and ABLE, which were also used in individuals with complete injuries.

Seven scales included an assessment of balance ability during walking; three of which focused solely on this task (DGI, Walking Romberg, Obstacle Clearance Test). As walking requires some lower extremity motor output, the DGI and Obstacle Clearance Test were used in individuals with motor incomplete injuries only. The severity of injury of the participants who completed the Walking Romberg test was not specified (Findlay, Balain, Trivedi, & Jaffray, 2009). Scales that included an assessment of balance during walking along with other tasks were the ABLE, Tinetti, Mini-BESTest, and CB&M.

The review did not identify any balance scale that assessed balance during a transfer task only; however, balance ability during some transfer activities such as lateral seated transfers, sit-

to-stand and/or stand-to-sit was assessed as part of the BBS, ABLE, Tinetti, mini-BESTest, and Balance CAT.

5.3.3 Clinical utility of the balance measures.

Of the 30 balance scales and balance groupings, 19 scored ≥8 on the clinical utility scale (Tyson & Connell, 2009), and thus were considered to have high clinical utility (see Table 5.2 for total scores, supplementary table S4 for score breakdown). The measures with high clinical utility were all balance scales intended for use in clinical environments such as the BBS, mini-BEST, and FRT. These measures are inexpensive and do not require specialist training or equipment; however, some require structures such as stairs and ramps, and this reduced their portability rating. All measures based on biomechanical constructs scored 0-2 on the clinical utility scale suggesting low clinical utility.

5.3.4 Comprehensiveness of clinical measures.

Components of balance captured by each balance scale are shown in Table 3. Some of the measures did not provide enough information to evaluate comprehensiveness, such as the T-shirt Test (Boswell-Ruys et al., 2009, 2010; Chen et al., 2003), Timed Standing (Chisholm et al., 2014), Timed Tandem Stance (Moriello et al., 2014), and Seated Reaction to Perturbation (Vilchis-Aranguren, Gayol-Merida, Quinzanos-Fresnedo, Perez-Zavala, & Galindez-Novoa, 2015). All other scales captured at least two components of balance and none captured all nine components. The mini-BESTest was the most comprehensive scale, as it captured all components except Functional Stability Limits. Each balance component was captured by at least one of the scales. Static stability was the most commonly assessed component (12 scales), whereas verticality was captured by only the mini-BESTest.

5.3.5 Psychometric properties.

At least one type of validity (construct, concurrent, discriminative, predictive, convergent, content, or criterion) and at least one type of reliability (test-retest, interrater, intra-rater, or internal consistency) was established in the SCI population for seven balance scales including BBS, FRT, ABLE, Test Table Test, Motor Assessment Scale, Sitting Balance Score, and CB&M (see Table 4). Reliability, but not validity, was established for the Tinetti Scale (Tamburella et al., 2014) in the SCI population. The psychometric properties of the BBS and

FRT have been established in individuals with wide spectrum of injury characteristics. For example, both measures have been validated in individuals with subacute (Boswell-Ruys et al., 2009; Datta, Lorenz, & Harkema, 2012; Lemay & Nadeau, 2010; Sprigle, Maurer, & Holowka, 2007) and chronic injuries (Sprigle, Wootten, Sawacha, & Thielman, 2003; Srisim et al., 2015; Wirz et al., 2010). Since most BBS items require standing without aids or braces, it has been used and validated in individuals with motor incomplete (AIS C & D) injuries. In contrast, FRT has been validated in individuals with motor complete (AIS A & B) (Adegoke, Ogwumike, & Olatemiju, 2002; Lynch, Leahy, & Barker, 1998) and incomplete (Field-Fote & Ray, 2010; Srisim et al., 2015) injuries. The BBS was shown to have interrater (Wirz et al., 2010) and intrarater (Tamburella et al., 2014) reliability, as well as construct (Datta et al., 2012) and concurrent (Lemay & Nadeau, 2010; Wirz et al., 2010) validity. However, the BBS was unable to predict those at risk of falls (Srisim et al., 2015; Wirz et al., 2010) or discriminate between those with tetraplegia and paraplegia (Lemay & Nadeau, 2010). The FRT was shown to have test-retest reliability by multiple researchers (Boswell-Ruys et al., 2009; Sprigle et al., 2007) and to possess interrater reliability (Srisim et al., 2015). With respect to validity, the FRT has convergent (Sprigle et al., 2007) and concurrent (Field-Fote & Ray, 2010) validity, and could predict those at risk of falling (Srisim et al., 2015). Only four (3%) studies evaluated the responsiveness of a balance scale in individuals with SCI (Datta et al., 2012; Datta, Lorenz, Morrison, Ardolino, & Harkema, 2009; Forrest et al., 2012; Tamburella et al., 2014). All four of these studies established the responsiveness of BBS in individuals with subacute or chronic motor incomplete (AIS C or D) SCI. Another study found the responsiveness of the Tinetti Scale to be low compared to that of the BBS in individuals with chronic AIS D SCI (Tamburella et al., 2014). In addition, one study also established the responsiveness of the seated FRT in individuals with early stages of their recovery; however the scale may have a ceiling effect (Forrest et al., 2012).

Table 5.3

Comprehensiveness of the clinical measures as per the modified Systems Framework for Postural Control (Sibley et al., 2015)

Measure	SS	UMS	FSL	V	RPC	APC	DS	SI	CI	Total
BBS	X	X	X			X	X	X		**6**
FRT		X	X			X				**3**
DGI		X				X	X	X	X	**5**
Tinetti	X	X	X		X	X	X	X		**7**
Mini-BESTest	X	X		X	X	X	X	X	X	**8**
ABLE	X	X	X		X	X	X	X		**7**
CTSIB	X	X						X		**3**
TTT	X	X	X			X				**4**
MAS	X		X			X				**3**
SBS	X				X					**2**
Romberg	X						*	X		**2 or 3**
CB&M	X	X				X	X	X	X	**6**
Balance CAT	X	X				X	X	X		**5**
BSSM	X		X							**2**
SOCT						X	X		X	**3**
Total	**12**	**10**	**7**	**1**	**4**	**11**	**8 or 9**	**9**	**4**	

* DS assessed in walking Romberg, but not in standing Romberg

SS: Static Stability; UMS: Underlying Motor Systems; FSL: Functional Stability Limits; V: Verticality; RPC: Reactive Postural Control; APC: Anticipatory Postural Control; DS: Dynamic Stability; SI: Sensory Integration; CI: Cognitive Influences; BBS: Berg Balance Scale; DGI: Dynamic Gait Index; Mini-BESTest: mini-Balance Evaluation Systems Test; FRT: Functional Reach Test; ABLE: Activity-Bases Level Evaluation ; CTSIB: Clinical Test of Sensory Organization and Balance; TTT: Test Table Test; MAS: Motor Assessment Scale; SBS: Sitting Balance Score; CB&M: Community Balance and Mobility; BSSM: Body Sway Using Sway Meter; SOCT: Standardized Obstacle Clearing Tests

Table 5.4

Types of validity and reliability tested for different non-biomechanical measures

Scale	Study	Population	Validity	Reliability
BBS	Datta et al., 2012	Subacute - chronic[b] AIS C - D	☑ Construct Principal Component Analysis	
	Lemay & Nadeau, 2010	Subacute - chronic[b] AIS D	☑ Concurrent Correlation with walking tests ☒ Discriminative No significant difference between individuals with paraplegia and tetraplegia	
	Wirz et al., 2010	Chronic[b] AIS A – D	☑ Concurrent Correlated with mobility measures, fear of falling and motor scores ☒ Predictive Could not differentiate fallers from non-fallers	☑ Interrater
	Srisim et al., 2015	Chronic[a] AIS C - D	☒ Predictive No significant difference between non-multiple fallers and multiple fallers	☑ Interrater
	Tamburella et al., 2014	Sub-acute - chronic[a] AIS D		☑ Intra-rater
FRT	Sprigle et al., 2007	Sub-acute - chronic[b] AIS levels not reported	☑ Convergent Correlation with ADL tasks ☑ Discriminative Differentiate between Cx from Tx and Lx impairment levels	☑ Test-retest
	BoswellRuys et al., 2009	Subacute - chronic[a] AIS A –D	☑ Discriminative Differentiate between higher (AIS A, C6-T7) from lower (AIS A-D, T8-L2) level impairments Differentiate between acute and chronic lesions	☑ Test-retest

	Lynch et al., 1998	Chronicity not reported[c] AIS A-B	☑ Discriminative Differentiate between individuals with C5-6 and T10-12, and between T1-4 and T10-12, but not between C5-C6 and T1-T4	☑ Test-retest
	Adegoke et al., 2002	Subacute – chronic[b] Complete and Incomplete (unable to stand)	☒ Discriminative No significant difference between three groups based on level of injury (C5-T1, T6-T8 and T10-L1)	☑ Test-retest
	Field-Fote & Ray, 2010	Chronic AIS C – D[a]	☑ Concurrent Correlation with COP excursion	☑ Test-retest
	Srisim et al., 2015	Chronic AIS C – D[a]	☑ Predictive Prediction of falls with 73% sensitivity and 75% specificity	☑ Interrater
	Sprigle et al., 2007	Chronic[a] AIS level not reported		☑ Test-retest
ABLE	Ardolino et al., 2012	Chronicity not reported[c] AIS C - D	☑ Content Through experts' opinion ☑ Construct Principal Component Analysis ☑ Discriminant Differentiate between 3 different groups – "walker", "stander", and "wheelchair-user"	☑ Internal Consistency
TTT	Pernot et al., 2011	Chronic[a] AIS A – D	☑ Criterion Correlation with "gold standard" balance perturbation task and COP excursion	☑ Interrater
MAS	Jorgenssen et al., 2011	Subacute – chronic[a] AIS A-D	☑ Convergent Correlation with injury level, AIS, and FIM scores	☑ Interrater

SBS	Jorgenssen et al., 2011	Subacute – chronic[a] AIS A-D	☑ Convergent Correlation with injury level, AIS, and FIM scores	☑ Interrater
CB&M	Chan et al., 2017	Subacute AIS C - D[a]	☑ Convergent Correlation with BBS, 6MWT, and 10mWT	☑ Internal Consistency
Tinetti	Tamburella et al., 2014	Subacute – chronic[a] AIS D		☑ Intra-rater

([*]clearly defined by authors; [‡]=not clearly defined by authors but defined based on time since injury data provided in study; [ǂ]=not defined in study nor were time since injury data provided). ☑ indicates that psychometric property was established. ☒ indicates that psychometric property was tested, but not established. [a]= clearly defined by authors; [b]=not clearly defined by authors but defined based on time since injury data provided in study; [c]=not defined in study nor were time since injury data provided.

BBS= Berg Balance Scale; FRT=Functional Reach Test; ABLE=Activity-Bases Level Evaluation; TTT=Test Table Test; MAS=Motor Assessment Scale; SBS=Sitting Balance Score; CB&M=Community Balance and Mobility; TSI = time since injury ($\leq$ 6 months: subacute; >6months: chronic).

Please refer to the publication for evidence and levels of psychometric properties

5.4 Discussion

Falls are a common occurrence among individuals with SCI, especially those with some sensorimotor function below the level of injury (Brotherton et al., 2007). A comprehensive and psychometrically-sound assessment of balance is crucial for the identification of those at risk of falling, and for the development and progression of rehabilitation programs. Here we completed a systematic review following PRISMA guidelines to describe the current state of the use of balance measures among the SCI population. A total of 127 studies were found to assess balance in individuals with SCI with all levels of neurological damage and injury severity represented. Thirty balance measures were identified; 11 measured a biomechanical construct, and 19 were balance scales primarily intended for use in clinical environments. The majority of studies were prospective assessments that provided adequate information about study inclusion and participant characteristics; however, about half of the studies recruited samples of convenience, thereby increasing the risk of bias in the research.

Among the studies that evaluated a biomechanical construct, measures of COP or COM were the most common and were used to evaluate balance across all tasks – sitting, standing, walking and transferring. Not surprisingly, all groupings of biomechanical constructs rated poorly on the scale of clinical utility (≤2/10) thereby limiting the likelihood of use in clinical environments. Among the balance scales identified in this review, the BBS was the most frequently used, followed by the FRT. Both had high clinical utility, but they were not the most comprehensive scales. Although both BBS and FRT have support for their validity (Datta et al., 2012; Lemay & Nadeau, 2010; Lynch et al., 1998; Sprigle et al., 2007), reliability (Lynch et al., 1998; Tamburella et al., 2014; Wirz et al., 2010) and responsiveness (Datta et al., 2012, 2009) among individuals with subacute and/or chronic SCI, the BBS was unable to predict falls in individuals with incomplete SCI (Srisim et al., 2015; Wirz et al., 2010). The FRT may have more promise as a means to predict falls in individuals with SCI as compared to the BBS (Srisim et al., 2015).

Ideally, a measure of balance for the SCI population will be comprehensive, psychometrically-sound and have high clinical utility. All balance scales identified in this review had high clinical utility (i.e. ≥8/10), but few had established psychometric properties in the SCI population, with the exception of the BBS and FRT, as detailed above. Further, most scales were lacking in comprehensiveness. The balance scales found to be the most comprehensive were the

Tinetti Scale, the mini-BESTest and the ABLE. The Tinetti Scale and ABLE evaluated seven of the nine domains of postural control, while the miniBESTest addressed eight. In contrast, most other balance scales used with individuals with SCI included five or fewer domains of postural control. As found in previous literature (Sibley et al., 2015), some balance domains (i.e. static stability, underlying motor systems, anticipatory postural control and sensory integration) were included in most scales. The domains of verticality, reactive postural control, and cognitive influences were less frequently incorporated into the balance scales, with only the mini-BESTest including all three. The mini-BESTest, however, lacks as assessment of sitting balance, whereas the Tinetti Scale and ABLE captured balance during all four tasks - sitting, standing, walking, and transferring.

Despite the comprehensiveness and high clinical utility of the mini-BESTest, ABLE and Tinetti Scale, their psychometric properties among the SCI population are not well-established. The Tinetti Scale does have high interrater reliability, but has low responsiveness among individuals with sub-acute and chronic AIS D SCI (Tamburella et al., 2014). One study established the validity (content, construct and discriminant) and internal consistency of the ABLE among individuals with incomplete and complete SCI (Ardolino, Hutchinson, Pinto Zipp, Clark, & Harkema, 2012). Another study published in June 2017 (i.e. after this review's search date) demonstrated internal consistency and high construct validity of the mini-BESTest among individuals with chronic AIS D SCI (Jorgensen, Opheim, Halvarsson, Franzen, & Roaldsen, 2017). Hence, the mini-BESTest and ABLE are promising measures of balance for clinical use with individuals with SCI, and the SCI-specific psychometric properties of these scales should be further established.

This systematic review evaluated 19 balance scales for the SCI population, whereas the SCI EDGE Task Force reviewed only seven balance measures (Kahn et al., 2016). The discrepancy likely resulted from the differing methodology used to identify balance measures used with this population and the differing search dates (i.e. our review includes more recent literature). As a result, our recommendations concerning the best-available balance measures to use clinically, as well as what knowledge gaps exist, differ from the SCI EDGE Task force (Kahn et al., 2016).

With respect to knowledge gaps, the results of this review highlight the need for further research and development in several areas of balance assessment for the SCI population.

However, our review has identified differing and more specific gaps than the work by Kahn and colleagues (Kahn et al., 2016). For example, Kahn et al. (Kahn et al., 2016) suggested that the field lacked a measure of ambulatory balance; however, our review identified seven scales that include assessment of walking balance. From the results of our systematic review, we have identified three gaps in balance assessment for individuals with SCI. First, the psychometric properties of the most comprehensive balance scales (i.e. Tinetti Scale, mini-BESTest and ABLE) should be further evaluated in individuals with sub-acute and chronic SCI. Second, as few studies to date have investigated the responsiveness of balance scales in individuals with SCI (Datta et al., 2012, 2009; Forrest et al., 2012; Tamburella et al., 2013), there is a need to identify balance scales that are responsive to change. Third, the development of a scale that evaluates balance during transfers in isolation is warranted. Transferring is an important functional task that is known to place wheelchair-users with SCI at risk of falls (Nelson et al., 2003). A measure of transfer skill for the SCI population was returned in the search (the Transfer Assessment Instrument (Tsai, Rice, Hoelmer, Boninger, & Koontz, 2013; You, Huang, & Huang, 2003)); however, it was excluded as it was deemed not to assess balance ability.

5.4.1 Study limitations.

There are a few study limitations to note. First, the reliance on samples of convenience in 54% of the studies places the findings at a greater risk of bias. Second, all but one of the included studies were written in English, even though we did not restrict the language in the search. This observation may suggest that the generalizability of the results is limited geographically.

5.5 Conclusion

In this review we identified the measures of balance that have been used with the SCI population, as well as areas of balance assessment for SCI in need of further research. To-date no single balance scale meets all criteria of a useful balance scale – high clinical utility, strong psychometric properties and inclusive of all domains of postural control (i.e. comprehensive). Following further evaluation of their psychometric properties in SCI population, the mini-BESTest and ABLE may fill this need.

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RELEVANCE OF CHAPTER FIVE TO THE THESIS

After understanding sensory integration, dynamic walking control, and reactive balance control in individuals with iSCI in the previous chapters, this chapter describes the current state of balance assessment measures available for individuals with SCI. An accurate and comprehensive assessment of balance control in clinical settings is necessary for identifying people at risk of falling and to monitor changes with rehabilitation over time; results of this study throw light on the clinical utility, psychometric properties, and different aspects of balance assessed by the currently available balance control measures in SCI population. Some clinical measures, like the Berg Balance Scale (Datta, Lorenz, & Harkema, 2012; Wirz, Muller, & Bastiaenen, 2010) and the Functional Reach Test (Boswell-Ruys et al., 2009; Sprigle, Maurer, & Holowka, 2007), have sound psychometric properties; however, they do not assess all balance domains as identified by the Systems Framework for Postural Control. The mini-Balance Evaluation Systems Test was found to be the most comprehensive measure (Sibley et al., 2015); however, further psychometric evaluation in the SCI population is required. The findings of this study also call for biomechanical validation of clinical measures, which is currently tested only by a few studies (such as Field-Fote & Ray, 2010; Pernot et al., 2011). This study clearly identifies gaps in the assessment of balance control in individuals with SCI in clinical settings.

CHAPTER SIX: GENERAL DISCUSSION AND CONCLUSIONS

Safe walking and fall prevention among individuals with SCI is likely to improve their quality of life and reduce the economic burden on the health care system. The goal for this thesis was to develop a better understanding of balance control in individuals with iSCI and to review how balance is assessed in individuals with SCI. A better understanding of balance assessment and control in the SCI population is a first step toward improved rehabilitation services for individuals with SCI.

The first, second and third objectives were focussed on understanding the potential of individuals with chronic iSCI to use different domains of balance control. Balance control is complex, and studying all the components of balance was beyond the scope of this thesis. We selectively chose to study the sensory integration, dynamic balance control, and movement strategies domains of Systems Framework For Postural Control (Horak, 2006).

The second chapter investigated the sensory integration component of balance control during quiet standing. This study looked at the effects of haptic input in the form of light fingertip touch on standing balance in individuals with chronic iSCI. The results of this study suggest that individuals with chronic iSCI have the potential to utilize the visual and additional haptic input to compensate for the loss of lower extremity sensations during quiet standing. Furthermore, the beneficial effect of light touch is correlated with the intact sensory function in the touch finger and the extent of impairment in the lower extremity sensation.

The third and fourth chapters investigated dynamic stability during walking, and reactive responses after an unexpected slip in individuals with chronic iSCI, respectively. The results suggest individuals with chronic iSCI are more stable than AB individuals due to their slower walking velocity, shorter step length, and the greater percentage of the gait cycle spent in double stance. Slower walking velocity was also found to be associated with a lower intensity of slip on an unexpected slip perturbation. This greater stability was observed only during normal walking and does not necessarily meant protection from falls once balance was perturbed as individuals with chronic iSCI were found to have less effective reactive responses including a slower onset of TA muscle activity and a smaller magnitude of trail side SOL muscle as compared to AB individuals. Strategies to achieve a greater stability during normal walking and limitations in

reactive responses among individuals with iSCI highlight limitations in their balance control, and a greater risk of falls.

To identify individuals at risk of falling, there is a need for comprehensive measures of balance control that have established psychometric properties and can be easily implemented in a clinical environment. The study in the fifth chapter systematically searched and reviewed all studies that have used a measure to assess balance control in individuals with SCI. Nineteen measures were found to have high clinical utility in terms of associated time, cost, specialized equipment/training, and portability. These measures can be easily used in clinical settings; however, our study identified gaps in the comprehensiveness and psychometric properties of these measures. The most commonly used measures (Berg Balance Scale and Functional Reach Test) have established psychometric properties but are not the most comprehensive. The more comprehensive measures (Mini-Balance Evaluation Systems Test and the Activity Based Level Evaluation Scale) need to be evaluated for their psychometric properties in individuals with SCI.

The findings from this thesis have a direct impact on SCI rehabilitation. The results emphasize the importance of comprehensive balance assessment and training for people with SCI who are at risk of falls. Assessment of stability during normal walking such as step width, percentage of gait in double stance, etc. can lead to a false impression of better balance control and lower chances of falls among individuals with iSCI. For example, older individuals with strategies for greater stability during walking were found to be at a greater risk of falls (Maki, 1997). Assessing reactive balance control; therefore, is of utmost importance to accurately identify individuals at risk of falls. Researchers and clinicians can benefit from the findings of the first study in selecting appropriate balance measures depending on the type(s) of activity (sit/stand/walk/transfer), and domain(s) of balance to be assessed. By establishing limitations in reactive balance, this study also opens up the avenues for testing the effectiveness of perturbation-based reactive balance training in individuals with iSCI, which has proven to be successful in older individuals (Pai & Bhatt, 2007), and individuals with stroke (Mansfield, Wong, Bryce, Knorr, & Patterson, 2015) and Parkinson's disease (Mansfield et al., 2015). Establishing the beneficial effects of light touch on standing balance paves the way to study the effects of haptic input during walking in individuals with iSCI and can help to design strategies and devices to provide additional sensory input for improving balance. For example, in patients

with stroke, a light touch cue provided through a cane can improve walking stability similar to that seen during heavy touch, but allows greater weight bearing through lower extremities (Boonsinsukh, Panichareon, & Phansuwan-Pujito, 2009). Effectiveness of haptic input in form of light touch in improving balance also call for further studies to try different forms of haptic input such as haptic anchors that consist of small weights connected to a cord and dragged on the floor (Hedayat, Moraes, Lanovaz, & Oates, 2017) for improving stability in individuals with iSCI.

6.1 Strengths, Limitations and Future Directions

Overall, these studies provide valuable information about balance control in individuals with iSCI. Including age-and-sex matched AB individuals as a control group allowed us study the effect of impairments on balance controlling for age and sex. We were able to obtain an unexpected slip in all participants except one, which allowed us to study true reactive responses. Unlike other studies that provide perturbations with a moving platform (Thigpen et al., 2009), our study used a slip device which is more similar to slips in real-life settings as the extent of perturbation is dependent on the walking behaviour of the individual. To study balance, we used various analyses - kinetic, kinematic, and EMG, which adds to the comprehensiveness of balance assessments that were included in this study.

There were some limitations in the studies, such as a small sample size due to the smaller population of individuals with iSCI in Saskatchewan. We also had difficulty finding age matched AB controls especially males over the age of 70 years. A small sample size could have led to a lack of significance in some of our between iSCI/AB group comparisons; however, the effect size for most of the comparisons was medium to large in our studies. In future, studies can involve multiple sites to obtain a larger sample size. The fear of falls being a predictor of future falls in individuals with iSCI (Jorgensen et al., 2017) means it can potentially have an effect on their balance control, which was not controlled for in our study. Future studies should measure and include the presence or absence of fear of falls in the participants, and include that in the analysis. The dimensions of the slip device may have limited the displacement of the slip; however, as compared to a previous study, participants appeared to have reached their maximum heel velocity post slip perturbation, which should have elicited the true reactive response (Cham & Redfern, 2002). The slip occurred only under one foot which makes it similar to stepping on a small patch of slippery surface, but it is different from stepping on other slippery surfaces (e.g.,

wet floors, skating/curling rinks, etc.) due to the size of slippery surface. In our studies we did not look at other forms of perturbations such as trip, which can be studied in the future studies. There is also a need of studying walking stability in environments that mimic the real world. A lot of biomechanical variables used to measure balance are dependent on velocity, so differences between the groups might be mediated by slower velocity in iSCI group; however, that is the normal behaviour of both groups which we wanted to study. All of the participants with iSCI had AIS D levels; therefore, the results cannot be generalized to all ambulatory individuals with iSCI. There is a need in future to study other sub-groups of SCI.

This thesis studied sensory integration, walking stability, and reactive strategies for balance control in individuals with iSCI. There are other components of balance such as proactive strategies, cognitive processing (involving attention and learning), limits of stability, orientation in space, etc. that need to be explored in this population. Future studies are also needed to see the effect of perturbation-based balance training to improve reactive balance in individuals with iSCI (Unger et al., 2018).

Overall, there is no single comprehensive measure with high clinical utility and established psychometric properties to assess balance in SCI population in clinical settings; however, the mini-BESTest and ABLE, upon establishment of psychometric properties in SCI population, may fill this gap. Individuals with chronic iSCI have the potential to use additional sensory information in form of light touch to improve standing balance. Clinicians can use this information to provide additional sensory information in form of light touch to improve standing balance in their patients who have adequate muscle strength to stand, but lack necessary sensory input about their body's orientation in space. Individuals with chronic iSCI adopt strategies for greater stability while walking, which could be to compensate for the limitations in their reactive balance. Clinicians can benefit from these findings by including assessment of reactive component of balance control. Assessing balance control during unperturbed walking may miss identifying individuals at risk of falls as individuals with iSCI are more stable when walking at a self-selected speed; however, when their balance is perturbed, they have limitations in their reactive responses. The findings of this thesis highlight the need for the assessment and rehabilitation of balance control after iSCI.

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APPENDICES

APPENDIX A. Sample Search Strategy for the Systematic Literature Review

PubMed

("Spinal Cord Injuries"[MeSH Terms] OR "spinal cord injuries" OR "spinal cord injury") AND ("Postural Balance"[MeSH Terms] OR "stability" OR "static balance" OR "dynamic balance" OR "walking balance" OR "sitting balance" OR "standing balance" OR "posture" OR "body equilibrium" OR "body posture" OR "unsteadiness" OR "balance impairment" OR "balance disorder" OR "balance") AND ("Humans"[MeSH Terms])

APPENDIX B. Ethics approval certificates

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Re-Approval

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Alison Oates	Kinesiology	13-184

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
Physical Activity Complex (PAC)
University of Saskatchewan
Saskatoon SK

SUB-INVESTIGATOR(S)
Kristin Musselman, Joel Lanovaz, A. Gary Linassi

STUDENT RESEARCHER(S)
Tarun Arora

FUNDER(S)
SASKATCHEWAN HEALTH RESEARCH FOUNDATION (SHRF)

TITLE
Investigating Walking Balance Control Following an Incomplete Spinal Cord Injury: A Pilot Study

RE-APPROVED ON	EXPIRY DATE
29-Jul-2014	28-Jul-2015

Delegated Review ☒ Full Board Meeting ☐

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This re-approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. This re-approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board has been approved by the Minister of Health, Province of Saskatchewan, to serve as a Research Ethics Board (REB) for research projects involving human subjects under section 29 of The Health Information Protection Act (HIPA).

Beth Bilson

Beth Bilson, Chair
University of Saskatchewan
Biomedical Research Ethics Board

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1607 – 110 Gymnasium Place
Saskatoon, SK Canada S7N 4J8

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Re-Approval

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Alison Oates	Kinesiology	13-184

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University of Saskatchewan
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STUDENT RESEARCHER(S)
Tarun Arora

FUNDER(S)
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29-Jul-2015	28-Jul-2016

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Chair, Vice-Chair or Delegate
University of Saskatchewan
Biomedical Research Ethics Board

R. Anne Springer, PhD MN BScN RN (CNS)
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INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
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STUDENT RESEARCHER(S)
Tarun Arora, Sarah Donkers, Hayley Legg, Janelle Unger

FUNDER(S)
SASKATCHEWAN HEALTH RESEARCH FOUNDATION (SHRF)

TITLE
Investigating Walking Balance Control Following an Incomplete Spinal Cord Injury

RE-APPROVED ON	EXPIRY DATE
15-Jul-2016	14-Jul-2017

Delegated Review ☒ Full Board Meeting ☐

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This re-approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
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REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Part C Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. Members of the Bio-REB who are named as investigators, do not participate in the discussion related to, nor vote on such studies when presented to the Bio-REB. This approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board has been approved by the Minister of Health, Province of Saskatchewan, to serve as a Research Ethics Board (REB) for research studies involving human participants under section 29 of The Health Information Protection Act (HIPA).

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Tarun Arora, Sarah Donkers, Hayley Legg, Janelle Unger

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TITLE
Investigating Walking Balance Control Following an Incomplete Spinal Cord Injury

RE-APPROVED ON	EXPIRY DATE
10-Jul-2017	09-Jul-2018

Delegated Review ☒ Full Board Meeting ☐

IRB 1 Registration #00001471 ☐ IRB 2 Registration #00008358 ☐ Not Applicable ☒

CERTIFICATION
The University of Saskatchewan Biomedical Research Ethics Board (Bio-REB) has reviewed the above-named research study. The study was found to be acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
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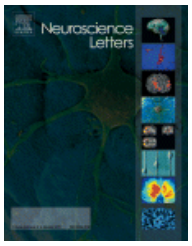
APPENDIX C. Copyright Permission



Title: Effect of haptic input on standing balance among individuals with incomplete spinal cord injury

Author: Tarun Arora,Kristin E. Musselman,Joel Lanovaz,Alison Oates

Publication: Neuroscience Letters

Publisher: Elsevier

Date: 6 March 2017

APPENDIX D. Supplementary Table S1

Citation	Type of study	Number of participants (SCI, able-bodied (AB))	Age (mean +/- 1SD (range)), years	Sex (males: females)	Neurological level of injury (range)	AIS Level /Completeness	Traumatic or Non-Traumatic SCI	Time Since Injury (mean +/- 1SD (range)), years
Adegoke et al.[1]	Prospective, cross-sectional	20 SCI	SCI: 42.7 +/- 9.4 (23.0 - 65.0)	SCI: 13 males : 7 females	C5 - L1	Compete and Incomplete, AIS not specified	Not specified	Group 1 = 2.46 +/- 3.42 Group 2 = 0.50 +/- 0.39 Group 3 = 1.7 +/- 1.92
Alexeeva et al.[2]	Prospective, RCT	35 SCI	SCI: 38.51 +/- 13.60 (19.0 - 63.0)	SCI: 30 males : 5 females	C2 - T10	C, D	Both	7.02 +/- 7.72 (1 - 37)
Allison & Singer [3]	Prospective, case study	1 SCI	26	male	C5	B	Traumatic	5.8
Altmann et al.[4]	Prospective, pyschometric	Total = 34 SCI = 20 Others = 14	Median (range) reported according to Trunk Impairment Classification score 0 TIC= 37 (18-52) 0.5 TIC= 36 (20-53) 1.0 TIC= 31(22-48) 1.5 TIC= 34(27-59)	Not Stated	Cervical = 9 Thoracic/Lumbar = 6 Not known (AIS C and D = 5)	A, B, C, D	not specified	Not specified
Amatachaya, Pramodhyakul & Srisim [5]	Prospective, cross-sectional	113 SCI	SCI: 52.4 (46.8 - 60.6)	SCI: 74 males: 39 females	Paraplegia and Tetraplegia	C, D	Both	Who Cleared Obstacles = 3.69 (2.86 - 4.52) Who Did Not clear: 4.65 (2.78 - 6.45)
Amatachaya, Pramodhyakul, Wattanapan, & Eungpinichpong.[6]	Prospective, cohort	94	Median (range): 53.5 (42.0-62.0)	62M: 32F	Tetraplegia = 26 Paraplegia = 68	C, D	Traumatic: 26 Non-Traumatic: 68	Median (range) = 3.0 (1.16-5.0)
Arazpour et al.[7]	Prospective, cross-sectional	5 SCI	SCI: 26.4 +/- 4.3	SCI: 4 males : 1 female	T8 - T12	A, B	Not specified	2.60 +/- 0.70
Ardolino et al.[8]	Prospective, psychometric	104 SCI	SCI: 38.6 +/- 15.0	SCI: 79 males : 25 females	Tetraplegia and Paraplegia	Compete and Incomplete, AIS not specified	Traumatic	3.73 +/- 5.65
Audu & Triolo.[9]		SCI: 9 AB: 9	SCI: 44.0 +/- 11.3 AB: 28.4 +/- 10.8	not stated	C6-C7: 3 T6-T7: 5 T10: 1	A, B, C	not specified	Not specified
Audu et al.[10]	Prospective, cross-sectional	5 SCI	SCI: 53.4 +/- 7.8 (42.0 - 61.0)	SCI: 3 males : 2 females	C7 - T10	A, B, C	Not Stated	0.84+/-0.36 (0.44 - 1.22)
Baardman et al.[11]	Prospective, case study	6 SCI	SCI: 38.8 +/- 11 (28.0 - 57.0)	SCI: 6 males	T4 - T12	A	Not specified	7.7 +/- 6.7 (3 - 21)
Bahrami et al.[12]	Prospective, cross-sectional	2 SCI, 10 AB	SCI: 34.5 +/- 6.4 (30.0 - 39.0) AB: 50.9 +/- 13.4 (26.0 - 33.0)	SCI: 1 male : 1 female AB: 7 males : 3 females	T8	Not specified	Not specified	Not specified
Barthelemy et al.[13]	Prospective, cross-sectional	24 SCI, 11 AB	SCI: 43.4 (20.0 - 64.0) AB: 45.0 (22.0 - 67.0)	SCI: 22 males : 2 females AB: 10 males : 1 female	C2 - L1	D	Both	(1.0 - 38.0)
Barthelemy, et al.,[14]	Prospective, cross-sectional	SCI: 25	43 +/- 14 (20 - 65)	23M : 2F	Cervical = 20 Thoracic = 4 Lumbar = 1	D	not specified	12 (1 - 38)
Behrman et al.[15]	Prospective, cohort	95 SCI	SCI: 43.0 +/- 17.0	SCI: 75 males : 20 females	Above T11	C, D	Both	(0.1 - 25.8)
Benedetti et al.[16]	Prospective, case study	3 SCI	SCI: 28.7 +/- 4.2 (24.0 - 32.0)	Not specified	T6 - T12	A	Not specified	3.69 +/- 1.12 (2.41 - 4.50)
Bernard et al.[17]	Prospective, cross-sectional	12 SCI, 6 AB	SCI: 29.9 +/- 2.8 (24.0 - 37.0) AB: 23.0 +/- 4.1 (17.0 - 28.0)	Not specified	T4 - L5	High: All Complete Low: 2 Incomp : 4 Complete AIS not specified	Not specified	injury date(year) mentioned time since injury: not specified
Betker et al.[18]	Prospective, case-studies	1 SCI 1 Spina bifida 1 Other (TBI)	SCI: 39	SCI: 1 male	T11-L1	A	Traumatic	0.83
Bishop et al.[19]	Prospective, case study	1 SCI	SCI: 22	SCI: 1 female	C5	D	Traumatic	4
Bjerkefors et al.[20]	Prospective, cross-sectional	10 SCI	SCI: 38.0 +/- 12.0	SCI: 7 males : 3 females	T3 - T12	A, B, C	Not specified	(3 - 26)
Bjerkefors et al.[21]	Prospective, case study	1 SCI, 1 AB	29	1 male	T3	A	Traumatic	3
Bolin et al.[22]	Prospective, case-studies	SCI = 4	25.75 ± 2.87 (22-28)	4M	C5-C6	A	Not specified	5.75 ± 2.50 (3-9)
BoswellRuys et al.[23]	Prospective, RCT	30 SCI	SCI: 44.0 +/- 12.5	SCI: 25 males : 5 females	T1 - T12	A, B	Not specified	Training group: 10 +/- 10 years post-injury; Control group: 19 +/- 13 years post-injury
BoswellRuys, et al.[24]	Prospective, psychometric	30 SCI	SCI: 35.0 +/- 11.0 (18.0 - 66.0)	SCI: 24 males : 6 females	C6 - L2	A, B, C, D	Not specified	9 +/- 12 (0.16 - 37)
Braz et al.[25]	Prospective, cross-sectional	4 SCI	SCI: 54.0 +/- 10.0	SCI: 4 males	T4 - T11	A	Not specified	9 +/- 5
Buehner et al.[26]	Prospective, cohort	225 SCI	SCI: 42.5 +/-15.9 (17.4 - 85.7)	SCI: 167 males : 58 females	Above T11	C, D	Not specified	2.60 +/- 4.04
Chaffin et al.[27]	Prospective, cross-sectional	5 SCI, 6 AB	SCI: (33.0 - 68.0) AB: (21.0 - 54.0)	SCI: 5 males AB: 3 males: 3 females	T4 - L4	A	Not specified	Not specified
Chan et al.,[28]	Retrospective, psychometric	30	38.3 ± 15.3 (16 - 64)	23M : 7F	Range: C1 - L4 Cervical = 17 Thoracic = 6 Lumbar = 5	C, D	16 Traumatic : 14 Non Traumatic	33.2 +/- 28.2 days (2-121 days)
Chen et al.[29]	Prospective, cross-sectional	30 SCI	SCI: 34.0 +/- 10.7 (20.0 - 57.0)	SCI: 27 males : 3 females	T3 - T12	A	Traumatic	(1.2 - 20)
Chisholm et al.[30]	Prospective, case study	2 SCI	SCI: 30.5	SCI: 2 males	C5 - S2	C	Traumatic	10.75
Cybulski & Jaeger[31]	Prospective, cross-sectional	4 SCI, 10 AB	SCI: 35.0 +/- 4.8 (31.0 - 42.0) AB: 32.3 +/- 8.0 (22.0 - 52.0)	SCI: 4 males AB: 6 males : 4 females	T1 - T12	Not specified	Traumatic	Not specified
Datta et al.[32]	Prospective, cohort	97 SCI	SCI: 38.0 +/- 17.0	SCI: 71 males : 26 females	Above T10	C, D	Both	0.99 (0.041 - 20.67)
Datta et al.[33]	Prospective, cohort	124 SCI	SCI: 42.0 +/-17.0	SCI: 96 males : 28 females	Above T11	C, D	Both	Median = 1 (0.1 - 25.8)
Day et al. [34]	Prospective, cross-sectional	10 SCI, 10 AB	SCI: 42.6 +/- 14.2 (21.0 - 66.0)	SCI: 6 males: 4 females	C4 - T6	D	Both	1.8 +/- 1.9 (0.5 - 6.5)
de Abreu et al.[35]	Prospective, cross-sectional	11 SCI, 6 AB	SCI: 30.7 +/- 3.4 (25.0 - 36.0) AB: 26.3 +/- 2.7	Not given	T2 - L1	A, C	Traumatic	5.50 +/- 5.02 (2 - 17)
Desrosiers, Nadeau, & Duclos.[36]	Prospective, cross-sectional	6 SCI, 7 AB	SCI: 59.0 +/- 7.0 (49.0 - 68.0) AB: 56.0 +/- 7.0 (50.0 - 70.0)	SCI: 6 males AB: 5 males : 2 females	C1 - L3	D	Both	1.43 +/- 1.94 years (0.1 - 5.19)
Ditunno et al.[37]	Prospective, psychometric	146 SCI	SCI: 32.0 (16.0 - 69.0)	SCI: 114 males : 32 females	C4 - L3	B, C, D	Traumatic	Less than 8 weeks Mean (SD) not stated
Field-Fote & Ray.[38]	Prospective, psychometric	Part 1: 10 SCI, 10 AB Part 2: 32 SCI	Part 1: SCI: 46.7 +/- 5.8; AB:41.4 +/- 13.6 ; Part 2: 44.9 +/- 1.2	Part 1: SCI: 8 males :2 females; AB = 6 males:4 females Part 2: SCI: 25 males:7 females	C3 - T12	C, D	Not specified	Part 1: 4.3 +/- 3.4 Part 2: 5.1 +/-6.0

Findlay et al.[39]	Prospective, cross-sectional	50 SCI	SCI: 61.5	Not given	C5 - C6	Not specified	Non-traumatic	Not specified
Forrest et al.[40]	Prospective, cohort	182 SCI	SCI: 41.0 +/- 17.0	SCI: 134 males : 48 females	C1 - T11	C, D	Both	(0.1 - 25.8)
Foster et al.[41]	Prospective, case study	1	28 years	F	C4	D	Traumatic	11
Freivogel et al.[42]	Prospective, case-studies	2 SCI 4 Others(2 Stroke and 2 TBI)	SCI: 24.0 +/- 18.38	SCI: 1 male : 1 female AB: 2 males : 2 females	T3 - T12	C	Not specified	SCI: 0.88 +/- 1.13
Fritz, S. et al.[43]	Prospective, cross-sectional	15 SCI	SCI: 44.5 +/- 13.3	SCI:10 males:4 females (Lower functioning group - 8 males:2 females; higher functioning group - 3 males:2 females)	Not specified	C, D	Not specified	Lower Functioning iSCI group: 6.6 +/- 6.3; Higher functioning iSCI group: 5.7 +/- 10.8
Fritz, S., et al.[44]	Prospective, case study	1 SCI 3 Others (1 Parkinsons, 1 CVA, and 1 Hemispherectomy)	SCI: 49.0	SCI: 1 female	L2	Incomplete, AIS not specified	Not specified	3
Gagnon et al.[45]	Prospective, cross-sectional	10 SCI	SCI: 41.2 +/- 8.8 (27.5 - 54.1)	SCI: 10 males	T4 - T11	A, B	Traumatic	9.90 +/- 12 (2.40 - 33.50)
Gao et al.[46]	Prospective, psychometric	9 SCI	SCI: 50.6 +/- 10.7 (35.0 - 63.0)	SCI: 3 males : 6 females	C6 - L1	B, C, D	Not Stated	17.22 +/- 13.94 (2 - 48)
Gauthier et al.[47]	Prospective, cross-sectional	21 SCI	SCI: 38.0 +/- 12.0 (21.0 - 58.0)	Not specified	C3 - L1	A, B, C, D	Not specified	3 +/- 5 (1 - 26)
Gauthier et al.[48]	Prospective, cross-sectional	15 SCI, 15 AB	SCI: 40.9 +/- 12.6 (23.2 - 57.9) AB: 39.3 +/- 12.6	SCI: 14 males : 1 female AB: 14 males : 1 female	C3 - L1	A, B, C, D	Not specified	4.21 +/- 6.1 (0.15 - 25.9)
Gillette et al.[49]	Prospective, cross-sectional	2 SCI, 5 AB	SCI: 35.0 AB: 28.8 +/- 7.6	SCI: 2 males	T4 - T6	A	Not specified	Not specified
Gillette et al.[50]	Prospective, cross-sectional	2 SCI, 18 AB	SCI: 35.0 AB: 32.0 +/- 5.2	SCI: 2 males AB: 9 males : 9 females	T4 - T6	A	Not specified	Not specified
Gorgey et al.[51]	Prospective, case study	1 SCI	SCI: 66.0	SCI: 1 male	C5 - C6	D	Traumatic	Not specified
Granat et al.[52]	Prospective, cross-sectional	6 SCI	SCI: 31.5 +/- 7.1 (20.0 - 40.0)	SCI: 3 males : 3 females	C3 - L1	C, D	Traumatic	7.33 +/- 5.85 (2 - 18)
Grangeon et al.[53]	Prospective, cross-sectional	14 SCI, 14 AB	SCI: 41.1 +/- 14.7 AB: 39.1 +/- 13.9	Not stated	C3 - L1	A, B, C, D	Not specified	4.36 +/- 6.34 (0.15 - 25.9)
Grigorenko et al.[54]	Prospective, RCT	12 SCI, 12 AB	SCI: 40.0 +/- 11 (22.0 - 57.0) AB: 32.8 +/- 8.3 (19.0 - 23.0)	SCI: 9 males : 3 females AB: 9 males : 3 females	T2-T11	A,B and C	Both	17.25 +/- 8.19 (4.0 - 32.0)
Harel et al.[55]	Prospective, cross-sectional	7 SCI, 7 AB	SCI: 41.9 +/- 13.8 AB: 34.0 +/- 13.3	SCI: 6 males : 1 female AB: 6 males : 1 female	T1 - T11	A, B	Not specified	7.86 +/- 5.09
Harkema et al.[56]	Prospective, cohort	196 SCI	SCI: 41.0 +/- 15.0	SCI: 148 males : 48 females	C1 - T11	C, D	Both	(0.1 - 25.8)
Harvey et al.[57]	Prospective, RCT	32 SCI	SCI: median = 27 (IQR 24 to 31)	SCI: 30 males : 2 females	T1 - L1	A, B, C	Not specified	median = 11 weeks (IQR 8 to 16)
Janssen_Potten et al.[58]	Prospective, cross-sectional	20 SCI, 10 AB	SCI: 36.9 +/- 10.1 (24.0 - 57.0) AB: 35.3 +/- 8.9 (22.0 - 54.0)	SCI: 28 males : 2 females	T2 - T12	A	Not specified	Not specified
Janssen-Potten et al.[59]	Prospective, cross-sectional	20 SCI, 10 AB	SCI: 34.9 +/- 8.9 (23.0 - 55.0) AB: 36.7 +/- 3.8 (27.0 - 41.0)	SCI: 28 males : 2 females	T2 - T12	A	Not specified	Not specified
Janssen-Potten et al.[60]	Prospective, cross-sectional	20 SCI, 10 AB	SCI: 39.3 +/- 9.9	SCI: 27 males : 3 females	T9 - L5	A	Not specified	Not specified
John, L. et al.[61]	Prospective, cross-sectional	15 SCI	SCI: (15.0 - 45.0)	SCI: 15 males	T8 - L1	A	Not specified	Not specified
Jorgensen et al.[62]	Prospective, cross-sectional	48 SCI	SCI: (18.0 - 69.0)	SCI: 37 males : 11 females	C5 - L1	A, B, C, D	Not specified	Median = 47 (0.25 - 48.0)
Kamper, Barin et al.[63]	Prospective, longitudinal	8 SCI, 5 AB	SCI: 33.8 +/- 6.0 (27.0 - 44.0) AB: 30.0 +/- 1.7 (29.0 - 33.0)	SCI: 13 males AB: 5 males	C5 - T9	A	Traumatic	13.6 +/- 9.0 (4.5 - 24.5)
Kamper, Parnianpour et al.[64]	Prospective, cross-sectional	8 SCI, 5 AB	SCI: 33.8 +/- 6.0 (27.0 - 44.0) AB: 30.0 +/- 1.7 (29.0 - 33.0)	SCI: 8 males AB: 5 males	C5 - T9	A	Traumatic	13.6 +/- 9.0 (4.5 - 24.5)
Karatas et al.[65]	Prospective, cross-sectional	16 SCI, 18 AB	SCI: 39.3 +/- 0.1 AB: 32.2 +/- 8.0	SCI: 9 males : 7 females AB: 8 males : 10 females	T1 - T12	Not specified	Not specified	0.9 +/- 0.8
Karcnik & Kralj[66]	Prospective, cross-sectional	5 SCI	Not Given	SCI: 4 males : 1 female	C4 - T5	Incomplete, AIS not specified	Not specified	2.06 +/- 2.47
Karimi et al.[67]	Prospective, cross-sectional	5 SCI, 5 AB	SCI: 31.6 +/- 7.1	SCI: 10 males	T12 - L1	Incomplete, AIS not specified	Not specified	7.90 +/- 6.57
Kim et al.,[68]	Prospective, cross-sectional	SCI = 30	46.0 ± 20.1 (10 - 75)	22M : 8F	Cervical = 14 Thoracic = 6 Lumbar = 10	A, B, C, D	Not specified	0.25 +/- 0.14
Kim, Chung, & Shin.[69]	Prospective, cross-sectional	7 SCI, 5 AB	SCI: 42.7 +/- 10.4 AB: 39.0 +/- 13.8	SCI: 9 males : 3 females	T5 - T12	A, B	Not specified	Not specified
Kizony et al.[70]	Prospective, psychometric	10 SCI, 12 AB	SCI: 33.6 +/- 12.4 AB: 29.6 +/- 9.5	SCI: 9 males : 4 females AB: 6 males : 6 females	T3 - L2	A, B, C	Both	(0.057 - 0.375)
Kubota et al.[71]	Prospective, psychometric	8 SCI 30 Others (Stroke, musculoskeletal, etc.)	SCI: 53.1 +/- 12.3	SCI: 6 males : 2 females	Not specified	Compete and Incomplete, AIS not specified	Both	3.15 +/- 1.80
Labruyere & van Hedel.[72]	Prospective, RCT	9 SCI	SCI: 59.0 +/- 11.0 (41.0 - 69.0)	SCI: 5 males : 4 females	C4 - T11	C, D	Both	4.16 +/- 4.70 (1.08 - 15.75)
Lee et al.,[73]	Prospective, cross-sectional	SCI = 10 AB =10	SCI: 46.7 +/- 8.5 AB: 42.2 +/- 10.2	SCI: 8M:2W AB: 5M:5W	Cervical	Incomplete, AIS not specified	Not specified	2.7 ± 6.3
Lemay & Nadeau[74]	Prospective, cohort, psychometric study	32 SCI	SCI: 47.9 +/- 12.8 (20.0 - 75.0)	SCI: 25 males : 7 females	C1 - L5	D	Both	0.2 +/- 0.12 (0.07 - 0.59)
Lemay & Nadeau[75]	Prospective, psychometric	32 SCI	SCI: 47.9 +/- 12.8 (20.0 - 75.0)	SCI: 25 males : 7 females	C1 - L5	D	Both	0.21 +/- 0.12
Lemay, Duclos, Nadeau, Gagnon & Desrosiers[76]	Prospective, cross-sectional	17 SCI, 17 AB	SCI: 54.1 +/- 15.5 AB: 53.9 +/- 21.0	Not Stated	Not Stated	D	Traumatic	1.03 +/- 0.53
Lemay, Duclos, Nadeau, & Gagnon[77]	Prospective, cross-sectional	12 SCI	SCI: 55.0 +/- 15.0 (26.1 - 71.5)	Not Stated	Not Stated	D	Not Stated	1.15 +/- 0.50 (0.44 - 2.03)
Lemay, Gagnon, Duclos, Grangeon, Gauthier, & Nadeau[78]	Prospective, cross-sectional	15 SCI, 14 AB	SCI: 52.7 +/- 17.0 AB: 40.2 +/- 13.8	Not specified	Not specified	D	Traumatic	0.84 +/- 0.59
Lemay, Gagnon, Nadeau, et al.[79]	Prospective, cross-sectional	16 SCI, 16 AB	SCI: 50.3 +/- 17.4 AB: 41.5 +/- 13.2	Not Stated	Not Stated	D	Traumatic	0.87 +/- 0.62 (0.04 - 2.03)
Liechti et al.[80]	Prospective, cross-sectional	8 SCI, 8 AB	SCI: 47.0 +/- 7.0 AB: 47.0 +/- 8.0	SCI: 8 males AB: 8 males	C4 - T8	D	Both	2.38 +/- 2.70
Lin, K., et al.[81]	Prospective, cross-sectional	7 SCI	SCI: 38.6 +/- 10.1 (23.0 - 53.0)	SCI: 6 males : 1 female	T7 - T12	A, B	Traumatic	7.87 +/- 6.6

Lorenz et al.[82]	Prospective, cohort	337 SCI	SCI: 40.0 +/-17.0	SCI: 255 males : 83 females	C1 - T12	C, D	Both	2.9 (0.1 - 52.3)
Lu, Lien, and Hsieh.[83]	Prospective, pyschometric	Total = 120 SCI = 4	Total = 72.0 +/- 12.7 SCI = not specified	Total: 63M:57F	Not specified	Not specified	Not specified	Not specified
Lynch et al. [84]	Prospective, psychometric	30 SCI	SCI: 30.8 +/- 7.2	SCI: 30 males	C5 - T12	A, B	Not specified	Not specified
Matjacic [85]	Prospective, case study	1 SCI	SCI: 32.0	SCI: 1 male	C5	D	Traumatic	1.08
Matsubara, Wu & Gordon [86]	Prospective, cross-sectional	10 SCI	SCI: 56.2 +/- 9.6 (41.0 - 72.0)	SCI: 9 males : 1 female	C2 - L3	D	Not Stated	9.1 +/- 5.7 (1.9 - 19.1)
Middleton et al.[87]	Prospective, cross-sectional	9 SCI, 9 AB	SCI: (24.0 - 47.0)	SCI: 9 males AB: 9 males	T5 - T12	A, B	Not specified	(1.8 - 22)
Mihelj & Munih [88]	Prospective, case study	1 SCI	Not given	Not specified	Not specified	Not specified	Not specified	Not specified
Milosevic et al.[89]	Prospective, cross-sectional	6 SCI, 10 AB	SCI: 41.3 +/- 18.1 (25.0 - 71.0) AB: 31.0 +/- 5.9 (25.0 - 41.0)	SCI: 6 males AB: 6 males : 4 females	C4 - C6	Compete and Incomplete, AIS not specified	Not Stated	12.33 +/- 9.87 (3 - 27)
Moriello et al.[90]	Prospective, case study	1 SCI	SCI: 57.0	SCI: 1 male	C3 - C6	D	Traumatic	0.67
Moriello et al.[91]	Prospective, case study	1	59	1 Male	C3-C6	D	Traumatic	2.67
Musselman et al.[92]	Prospective, case study	4 SCI	SCI: 43.5 +/- 15.3	SCI: 2 males : 2 females	C5 - L1	C	Traumatic	median = 2.7 IQR = 12.8
Nataraj et al.[93]	Prospective, case study	1 SCI	SCI: 54.0	SCI: 1 female	T4	A	Not specified	Not specified
Parkinson, Reed & Chaffin.[94]	Prospective, cross-sectional	9 SCI, 9 AB	Not given	Not specified	T4 - L4	A	Not specified	Not specified
Pernot et al.[95]	Prospective, psychometric	20 SCI 13 Others (10 Amputation 1 CP, 1 Post-polio, 1 Dystrophia)	SCI: 47.6 +/- 12.5 (18.0 - 64.0)	SCI: 13 males : 7 females	T3 - S5	A, B, C, D	Not specified	9.9 +/- 8.5 (2.5 - 35)
Potten et al.[96]	Prospective, cross-sectional	20 SCI, 10 AB	SCI: 34.9 +/- 8.9 (23.0 - 55.0) AB: 36.7 +/- 3.8 (27 - 41)	SCI: 28 males: 2 females	T2 - T12	A	Traumatic	Not specified
RoopchandMartin & Bateman [97]	Prospective, case study	2 SCI	SCI: 23.0	SCI: 2 males	T4 - T12	A	Traumatic	0.25
Saraf et al.[98]	Prospective, cross-sectional	50 SCI	SCI: 44.5 +/- 14.5	SCI: 36 males : 14 females	14 high tetraplegia, 23 low tetraplegia, 13 paraplegia Exact levels not defined	C, D	Not specified	7.08 +/- 7.04
Sayenko et al.[99]	Prospective, cohort	6 SCI	SCI: 41.0 +/- 13.2	SCI: 5 males : 1 female	C4 - T12	C, D	Not specified	9.2 +/- 7.4
Scivoletto et al.[100]	Prospective, cross-sectional	65 SCI	SCI: 46.1 +/- 16.8 (18.0 - 77.0)	SCI: 44 males : 21 females	C1 - L5	A, B, C, D, E	Both	3.54 +/- 3.83
Seelen et al.[101]	Prospective, cross-sectional	30 SCI, 15 AB	SCI: 35.6 +/- 9.0 (26.0 - 55.0) AB: 34.8 +/- 10.0 (22.0 - 56.0)	SCI: 27 males : 3 females AB: 14 males : 1 female	T2 - T12	A	Not specified	Not specified
Seelen et al.[102]	Prospective, cross-sectional	30 SCI, 15 AB	SCI: 35.5 +/- 9.0 (24.0 - 55.0) AB: 34.8 +/- 10.0 (22.0 - 56.0)	SCI: 41 males : 4 females	T2 - T12	A	Not specified	Not specified
Seelen, Potten, Adam, Drukker, Spaans & Huson.[103]	Prospective, longitudinal	12 SCI	SCI: 36.3 +/- 9.5 (17.0 - 46.0)	SCI: 10 males : 2 females	T2 - T12	A	Not specified	2.9 +/- 1.1 (1.5 - 4.2)
Seelen, Potten, Drukker, Reulen, & Pons.[104]	Prospective, longitudinal	12 SCI	SCI High: 28.6 +/- 9.0 (22.0 - 45.0) Low: 34.0 +/- 10.0 (17.0 - 46.0)	SCI: 10 males : 2 females	T2 - T12	A	Traumatic	2.9 +/- 1.1 (1.5 - 4.2)
Serra-Ano et al.[105]	Prospective, cross-sectional	24 SCI, 24 AB	SCI: 40.3 +/-8.8 years AB: 27.7 +/-12.6 years	SCI: 21 males : 3 females AB: 14 males : 10 females	T4 - L1	A, B	Not specified	14.2 +/- 8.70
Shin & Sosnoff [106]	Prospective, cohort	18 SCI, 18 AB	SCI: (19.0 - 27.0)	SCI: 9 males : 9 females AB: 9 males : 9 females	T4 - L4	A, C, D	Not specified	Not specified
Shirado et al.[107]	Prospective, cross-sectional	13 SCI, 11 AB	SCI: 29.8 +/- 4.2 (22.0 - 39.0) AB: 32.3 +/- 5.5 (24.0 - 36.0)	SCI: 11 males : 2 females AB: 6 males : 5 females	T5 - T12	A	Traumatic	1.62 +/- 0.56 (1.0 - 2.33)
Sprigle et al.[108]	Prospective, cross-sectional	SCI = 22	(18 - 64)	19M	C5 and below	AIS not specified ASIA score = 65-247	Not specified	Not specified
Sprigle et al.[109]	Prospective, psychometric	40 SCI	SCI Group 1: Median = 33.0 (15.0 - 58.0) Group 2: Median = 23.5 (16.0 - 32.0)	SCI Group 1: 16 males:4 females Group 2: 15 males : 5 females	C5 - T12	Not specified	Traumatic	SCI Group 1: Median = 4.29 (0.91 - 20.17) Group 2: Median = 0.28 (0.11 - 0.58)
Srisim, Amatachaya & Saengsuwan.[110]	Prospective, cohort	83 SCI	SCI: 48.6 +/- 10.9	SCI: 56 males : 27 females	Non-multiple fallers = 17 Tetra:43 Para Multiple fallers = 12 Tetra:11 Para	C, D	Both	Non-multiple fallers = 3.89 +/- 3.03 Multiple fallers = 4.89 +/- 5.00
Stevens et al.[111]	Prospective, pre-test post test	11 SCI	SCI: 47.7 +/- 13.6 (23.0 - 64.0)	SCI: 7 males : 4 females	C2 - T8	C, D	Traumatic	4.82 +/-7.81 (1 - 28)
Tamburella et al. [112]	Prospective case study with retrospective matched control	12 SCI, 6 AB	SCI: 52.8 +/- 12.5 (36.5 - 67.0) AB: 50.3 +/- 10.2 (37.0 - 61.0)	SCI: 6 males : 6 females AB: 3 males : 3 females	T5 - L5	D	Both	(1.17 - 4.25)
Tamburella, Scivoletto, Iosa, & Molinari. [113]	Prospective, RCT	11 SCI	SCI: 51.6 +/- 15.5	SCI: 6 males : 5 females	C6 - T11	D	Both	5.72 +/- 3.19 (2-12)
Tamburella, Scivoletto, Iosa, & Molinari. [114]	Prospective, psychometric	23 SCI	SCI: 48.3 +/- 15.9 (19.0 - 84.0)	SCI: 14 males : 9 females	C5 - L5	D	Both	Median = 1.37 (0.42 - 6.25)
Thigpen et al. [115]	Prospective, cross-sectional	8 SCI, 8 AB	SCI: 47.1 +/- 17.3 (19.0 - 74.0) AB: 45.8 +/- 15.3 (20.0 - 72.0)	SCI: 7 males : 1 female AB: 7 males : 1 female	C4 - T5	D	Not specified	1
Tokita et al. [116]	Prospective, cross-sectional	5 SCI, 30 AB Others - 72 (12 unilateral and 14 bilateral labrynthine loss, 8 basal ganglia, 14 cerebral, 7 brain stem and 17 cerebellar lesions.	Not specified	Not specified	Not specified	Not specified	Cervical myelopathia = 3 SMON = 1 Syringomyelia = 1	Not specified
Triolo et al. [117]	Prospective, case study	1 SCI	SCI: 14.0	SCI: 1 male	C4	A	Traumatic	20
Triolo et al. [118]	Prospective, case study	8 SCI	SCI: (26.0 - 58.0)	SCI: 6 males : 2 females	C5 - T10	A, B, C	Not specified	11.5 +/- 6.9 (5.8 - 26.5)
Tsang et al. [119]	Prospective, cross-sectional	11 SCI, 8 AB	SCI: 46.2 +/- 11.8 AB: 49.1 +/- 10.3	SCI: 7 males: 4 females AB: 7 males : 1 female	C6 - L1	B, C, D	Not Stated	Control = 17.3 +/- 7.8 Treatment = 14.7 +/- 13.7
Vilchis-Aranguren et al. [120]	Prospective, longitudinal	14	31.8 +/- 7.81 (22 - 47)	9M: 7F	C5 - L1	ompete and Incomplete, AIS not specifie	Not specified	wheelchair use history 10.1 +/- 7.27 (3 - 26)
Villiger et al. [121]	Prospective, cross-sectional	9 SCI, 14 AB	SCI: 55.1 +/- 15.8 (28.0 - 71.0) AB: 47.1 +/- 14.4 (25.0 - 61.0)	SCI: 5 males : 4 females AB: 7 males : 7 females	C4 - T12	D	Both	3.22 +/- 1.39 (1 - 5)
Wall et al. [122]	Prospective, pre-test post test	5	58.6 +/- 5.18 (50 - 64)	5 males	C5 - L1	D	Traumatic	7.60 +/- 5.27 (1 - 15)
Wannapakhe et al. [123]	Prospective, Cohort	50 SCI	SCI: 47.7 +/- 13.8	SCI: 37 males : 13 females	Not specified	C, D	Traumatic	3.07 +/- 3.32

Wirz, Muller, & Bastiaenen. [124].	Prospective, retrospective, cross-sectional	43 SCI	SCI: 49.3 +/- 11.5 (24.0 - 65.0)	SCI: 33 males : 9 females	C1 - L5	A, B, C and D	Both	5.54 +/- 5.52 (1 - 35.5)
Wu et al. [125]	Prospective, RCT	10 SCI	SCI: 47.0 +/- 7.0 (34.0 - 58.0)	SCI: 8 males : 2 females	C2 - T10	D	Not specified	(1.3 - 13.5)
Wydenkeller et al. [126]	Prospective, cross-sectional	6 SCI, 6 AB	SCI: 57.0 +/- 9.0 AB: 57.0 +/- 10.0	SCI: 6 males AB: 6 males	Not specified	D	Not specified	Not specified
Yu et al. [127]	Prospective, cross-sectional	10 SCI	SCI: 47.8 +/- 13.4 (26.0 - 72.0)	SCI: 9 males : 1 female	C4 - T11	D	Not specified	3.84 +/- 5.72 (0.25 - 19.17)

APPENDIX E. Supplementary Tables S2

Citation	Reason for Balance Assessment	Biomechanical or Non-Biomechanical Measure	Biomechanical Measure Category 1) Gait variables: speed, cadence, stride/stride length, stride/stride length variability, stance phase, double-support time) 2) COP/COG related measures: COP distance measure ---- COP area measure --- COP velocity measure --- COP variability measure (RMS) --- COP frequency measure --- Margin of Stability --- other measures derived from COP/COM 3) Joint angles 4) EMG 5) Reachlmr distance	NON-BIOMECHANICAL measure(s) used
Adegoke et al.[1]	> to investigate differences in dynamic balance of patients with different levels of spinal cord injury > to investigate intraclass coefficient of the modified functional reach test	Non-Biomechanical	N/A	> FRT
Alexeeva et al.[2]	> to compare the effect of 3 forms of training (TRK, TM and PT) on balance (along with other measures)	Non-Biomechanical	N/A	> Tinetti Scale
Allison & Singer [3]	> to investigate the biomechanical and functional adaptations during reaching and transfer tasks	Biomechanical	> COP distance measure > COP frequency measure	N/A
Altmann et al.[4]	to validate the Trunk Impairment Classification (TIC) by comparing sitting balance scores between participants of different impairment groups	Biomechanical	> COP distance measure > COP area measures > Forces/Torques: maximum isometric force in trunk muscle strength	N/A
Amatachaya, Pramodhyakul & Srisim [5]	> to compare balance ability between participants who pass and failon an obstacle crossing task	Non-Biomechanical	N/A	> Ability to Cross Obstacles
Amatachaya, Pramodhyakul, Wattanapan, & Eungpinichpong.[6]	to test the relationship between failure on obstacle clearing and occurrence of falls	Non-Biomechanical	N/A	> Ability to Cross Obstacles
Arazpour et al.[7]	> to investigate the influence of ankle joint motion on postural stability and walking in people with SCI when using an orthosis	Biomechanical	> COP distance measure	N/A
Ardolino et al.[8]	> to develop a new balance outcome measure speficic to SCI population > to determine psychometric properties of the new scale using Rasch analysis	Non-Biomechanical	N/A	> ABLE
Audu & Triolo.[9]	to determine the extent of active and passive control mechanisms of seated balance	Biomechanical	> Joint angles: pelvic and trunk angle > others: trunk stiffness	N/A
Audu et al.[10]	> to test a FNS based feedback control system that was developed for control of seated balance in individuals with SCI	Biomechanical	> Joint angle: Trunk tilt as obtained using accelerometers and time taken to bring the angle back to a certain state	N/A
Baardman et al.[11]	> to compare functional standing performance in the Advanced Reciprocating Gait Orthosis (ARGO) with and without hip joint link	Biomechanical	> COP distance measure > other measures derived from COP: time taken to return the position signal value to close to the value just prior to the perturbation	N/A
Bahrami et al.[12]	> to compare stability (among other measures) during the sit-to-stand transfer in the healthy and paraplegic subjects.	Biomechanical	> COP/COM distance measure > others: linear momentum in vertical and horizontal directions	N/A
Barthelemy et al.[13]	> To determine correlation between a balance measure (in addition to other measures) and maximum toe elevation during walking	Non-Biomechanical	N/A	> BBS
Barthelemy, et al.,[14]	to correlate transmission in descending pathways using imaging and electrophysiological techniques with balance measures (among other measures)	Non-Biomechanical	N/A	> BBS
Behrman et al.[15]	> to evaluate baseline variability in performance and recovery in balance (along with other measures) measures following a therapeutic intervention	Non-Biomechanical	N/A	> BBS
Benedetti et al.[16]	> to evaluate the effect of training on postural control in the upright position in paraplegic patients who were using advanced reciprocating gait orthoses	Biomechanical	> others: fall threshold based on peak velocity and size of the platform excursion	N/A
Bernard et al.[17]	> to assess the ability of paraplegics to obtain trunk balance under dynamic stresses, and > to analyze the various balance strategies according to the level of lesion	Biomechanical	> others: dampning factor - subject's ability to maintain head at the lowest level of acceleration following a perturbation	N/A
Betker et al.[18]	> to describe rehabilitation protocol using COP-controlled video game-based tool for the maintenance of balance in a short-sitting position in individuals with SCI	Non-Biomechanical	N/A	> CTSIB
Bishop et al.[19]	> to document benefits ofrobotic gait training on BBS scores (among other functional measures) in an individual with iSCI	Non-Biomechanical	N/A	> BBS
Bjerkefors et al.[20]	> to determine the influence of training on a modified kayak ergometer on postural responses to support surface translations in persons with long-standing SCI	Biomechanical	> Joint angles: trunk angular and linear displacement in AP and ML directions	N/A
Bjerkefors et al.[21]	> to investigate activation of upper body muscles, including deep abdominal muscles in reaction to unexpected balance perturbations	Biomechanical	> EMG (surface and intra-muscular): onset times and patterns	N/A
Bolin et al.[22]	to study the effect of sitting position on sitting balance (along with other measures)	Non-Biomechanical	N/A	> FRT
BoswellRuys et al.[23]	> to evaluate the effectiveness of a 6-week task-specific training programme on ability to sit unsupported	Non-Biomechanical	N/A	> FRT > Timed Dressing/Undressing
BoswellRuys, et al.[24]	> to devise a battery of tests to assess abilities of individuals with SCI to sit unsupported > to examine the reliability of these tests in people with SCI > to assess the correlation of the measures > to determine the validity of the tests by assessing their ability to detect differences in neurologic level of SCI and time since injury	Non-Biomechanical	N/A	> using the Lord Sway Meter to calculate sway and reach > FRT > Timed Dressing/Undressing
Braz et al.[25]	> to evaluate stability during FES neuroprosthesis assisted standning in order to compare different strategies of stimulation - hand controlled operation and using kinematic feedback strategies	Biomechanical	> other measure derived from COP: stability zones based on COP position relative to the base of support area	N/A
Buehner et al.[26]	> to identify the effect of locomotor training on BBS (among other measures) and > as a secondary objective to see if pretraining ISNCSCI measures are related to locomotor and balance performance after locomotor training	Non-Biomechanical	N/A	> BBS
Chaffin et al.[27]	> Describe "motion dynamics" when seated and moving weighted objects in workspace	Biomechanical	> COP distance measure	N/A
Chan et al.,[28]	to validate the Community Balance and Mobility Scale (CB&M) and establish it's internal consistency in individuals with iSCI during inpatient rehabilitation	Non-Biomechanical	N/A	> BBS > CB&M
Chen et al.[29]	> to compare the sitting stability between patients with high and low thoracic SCI > to determine factors that can predict sitting stability; and > to examine the relation between injury level, sitting stability, and functional performance.	Both	> COP distance measure > COP variability measure	> Timed Dressing/Undressing
Chisholm et al.[30]	> to evaluate the feasability of a sensory tongue stimulation with balance and gait training on balance(along with other functional outcomes) in people with iSCI	Non-Biomechanical	N/A	> Timed Standing
Cybulski & Jaeger[31]	> to quantitatively measure standing balance under different conditions and studying how vision and upper extremity information contribute to maintenance of upright posture in healthy and paraplegic subjects	Biomechanical	> COP distance measure > COP frequency measure	N/A
Datta et al.[32]	> to perform principal components analysis of the BBS in patients with motor incomplete (AIS C or D) SCI in order to evaluate it utility in the SCI population	Non-Biomechanical	N/A	> BBS
Datta et al.[33]	> to evaluate the utility of the Berg Balance Scale among patients with motor incomplete spinal cord injuries (SCIs) > to determine how the utility of the Berg Balance Scale changes over time with activity- based therapy, > to identify differences in scale utility across patient groups defined by status of recovery.	Non-Biomechanical	N/A	> BBS
Day et al. [34]	> Examine walking balance through foot placement variability > Assess relationship between measures of variability & clinical balance assessments > Determine if spatial parameter variability can be used as a clinical correlate for complex balance measurements	Both	> Gait variables: Step length/width variability > other measure derived from COP: Margin of Stability	> BBS > DGI
de Abreu et al.[35]	> to evaluate the influence of different types of wheelchair seats on postural control of individuals with paraplegia	Biomechanical	Reaching Distance: Trunk anterior displacement	N/A
Desrosiers, Nadeau, & Duclos.[36]	> to study the postural adaptations during overground walking on level and inclined surfaces.	Both	> Forces/Torques: Stabilizing and Destabilizing forces calculated from kinematic and kinetic data	> BBS
Ditunno et al.[37]	> to correlate improvements in BBS (in addition to other measures of walking function) with WISCI scores	Non-Biomechanical	N/A	> BBS
Field-Fote & Ray.[38]	> to test validity and reliability of the SRT (seated reach test) in measuring seated postural control in individuals with motor iSCI	Biomechanical	> COP distance measure > Reaching distance: wrist and trunk excursion	N/A
Findlay et al.[39]	> to determine if performing the Romberg while walking is more sensitive than the traditional Romberg test for identifying cervical myelopathy.	Non-Biomechanical	N/A	> Romberg's Sign
Forrest et al.[40]	> to examine the relationships among the 6-minute walk, 10-meter walk, Berg Balance Scale, and Modified Functional Reach in response to standardized locomotor training in individuals with incomplete SCI > to assess whether the relationships among the measures are dependent on the level of functional ability as assessed using Neuromuscular Recovery Scale (NRS)	Non-Biomechanical	N/A	> BBS > FRT
Foster et al.[41]	to describe the effects of backward walking training on balance (along with other measures)	Both	sensory organization test using computerized dynamic	> BBS
Freivogel et al.[42]	> to evaluate effects of a newly developed electromechanical gait device (LokoHelp, Medburg Basel) on postural control and balance (in addition to other parameters)	Non-Biomechanical	N/A	> BBS
Fritz, S. et al.[43]	> to evaluate the effects of intensive mobility training on gait, balance, and mobility in individuals with iSCI	Non-Biomechanical	N/A	> BBS > DGI

Fritz, S., et al.[44]	> to see improvements in balance (along with other gait and mobility) with intensive mobility training	Non-Biomechanical	N/A	> BBS > DGI
Gagnon et al.[45]	> to measure dynamic stability requirements during sitting pivot transfers	Biomechanical	> Forces/Torques: Stabilizing and Destabilizing forces calculated from kinematic and kinetic data	N/A
Gao et al.[46]	> to assess dynamic sitting balance using a newly developed tool, and > to test the reliability and validity of the new tool for measuring the dynamic sitting balance of wheelchair users with spinal cord injury	Biomechanical	> COP distance measure > other measures derived from COP: directional control of COP and reaction time	N/A
Gauthier et al.[47]	> Determine the direction of trunk inclincation that predicts multidirectional postural stability while seated	Biomechanical	> COP distance measure > COP area measure > other measures derived from COP: specific stability index and overall stability indexes	N/A
Gauthier et al.[48]	> to compare multidirectional seated postural stability between individuals with and without SCI > to evaluate the effects of back and abdominal muscles on multidirectional seated postural stability by comparing individiduals who have partial or complete innervations of their low back and abdominal muscles to those who have complete paralysis > to verify if individuals with SCI who have partial or complete innervations of their low back and abdominal muscles had multidirectional seated postural stability ability similar to healthy controls.	Biomechanical	> COP distance measure > COP area measure > other measures derived from COP: direction specific stability index and overall stability index	N/A
Gillette et al.[49]	> to document a variety of COP measures during standing > to compare AB and FNS standing > to relate various measures to overall quality of standing performance	Biomechanical	> COP distance measure > COP velocity measure > COP frequency measure	N/A
Gillette et al.[50]	> to compare postural parameters during quiet standing between able-bodied individuals, and individuals with SCI that stood using functional neuromuscular stimulation.	Biomechanical	> COP distance measure	N/A
Gorgey et al.[51]	> to determine the effects of locmotor training programs on BBS (along other measures)	Non-Biomechanical	N/A	> BBS
Granat et al.[52]	> to evaluate theapeutic effects of an FES gait programme on standing balance measure (among other measures) in iSCI patients	Biomechanical	> COP velocity measure > COP area measure	N/A
Grangeon et al.[53]	> to compare quasi-static postural stability between individuals with SCI and healthy controls during short-sitting positions > to evaluate the association between demographics and clinical measures (sensorimotor impairments and time since injury), and quasi-static seated postural stability measures	Biomechanical	> COP distance measure > COP velocity measure > COP area measure > COP frequency measure	N/A
Grigorenko et al.[54]	> to compare sitting balance in SCI and AB individuals and to evaluate the effects of a period of open sea kayak training on sitting balance in a group of people with SCI	Biomechanical	> COP distance measure > COP velocity measure > COP variability measure > COP frequency measure	N/A
Harel et al.[55]	> to measure the sensitivity of a computerized posturography system (Neurocom Smart EquiTest) to injury and lesion level in comparison to other commonly used clinical tests incldluing BBS and MFRT.	Both	> COP distance measure > other measures derived from COP: limits of stability + CTSIB components	> BBS > FRT
Harkema et al.[56]	> to evaluate the effects of intensive locomotor training on balance and ambulatory function in individuals with iSCI	Non-Biomechanical	N/A	> BBS
Harvey et al.[57]	> to assess the effects of an "intensive motor training program directed at improving the ability to sit unsupported"	Non-Biomechanical	N/A	> FRT
Janssen_Potten et al.[58]	> to study the effect of seat tilting on balance control measure (amont other measures) in persons with a thoracic spinal cord injury	Both	> COP distance measure > EMG > Joint angle (pelvic tilt)	> FRT
Janssen-Potten et al.[59]	> to study whether chair configuration influences sitting balance in persons with spinal cord injury	Both	> COP distance measure > EMG: mean rectified activity	> FRT
Janssen-Potten et al.[60]	> to investigate if foot rests contribute to active control of sitting balance	Both	> COP distance measure > EMG: mean rectified activity over fixed time intervals > others: reactiontime/movement time	> FRT
John, L. et al.[61]	> to estimate the effect of fear of falling on postural control of individuals with paraplegia using KAFO > to explore the relationship between postural conrol and gait parameters in individuals with paraplegia	Biomechanical	> COP distance measure > COP velocity measure	N/A
Jorgensen et al.[62]	> to assess inter-rater reliability and validity of two measures - the Motor Assessment Scale and the Sitting Balance Score	Non-Biomechanical	N/A	> MAS > SBS
Kamper, Barin et al.[63]	> to examine the lateral postural stability of seated individuals with SCI in dynamic environment	Biomechanical	> COP distance measure > COP velocity measure > other measures derived from COP: FLCOP and DFLCOP > Forces/Torques: estimates of joint torques, segment angles and trajectories	N/A
Kamper, Parnianpour et al.[64]	> to examine postural stability of individuals with spinal cord injury when exposed to external perturbation	Biomechanical	> COP distance measure > other measures derived from COP: fraction of limit of COP	N/A
Karatas et al.[65]	> Evaluate center-of-pressure displacement in sitting > Investigate relationship between dynamic sitting stability & pressure ulcers	Biomechanical	> COP distance measure	N/A
Karcnik & Kralj [66]	> to discuss mutual dependance of crutch-assisted gait velocity and stability from a biomechanical perspective	Biomechanical	> other measures derived from COP - Relative Kinematic Stability Index and Absolute Dynamic Index	N/A
Karimi et al.[67]	> to evaluate the standing performance of individuals with paraplegia whiled using a new orthosis - Mohammad Taghi Karimi Reciprocal Gait Orthosis (MTK-RGO)	Biomechanical	> COP distance measure > COP velocity measure	N/A
Kim et al.,[68]	to evaluate correlation between K-BBS with WISCI and SCIM	Non-Biomechanical	N/A	> BBS
Kim, Chung, & Shin. [69]	> to examine the effect of goal-oriented training on an unstable surface on the sitting balance ability of patients with spinal cord Injury	Both	> COP velocity measure > COP area measure > other measures derived from COP: angle of sway from COM (results not reported)	> FRT
Kizony et al.[70]	> to examine relationships between static balance test performance and performance within the virtual environments (VEs) > to compare performances within the VEs between participants with SCI and able-bodied participants	Non-Biomechanical	N/A	> FRT
Kubota et al.[71]	> to assess changes in balance ability after a rehabilitation training with a new robot to evaluate the feasibility of the training	Non-Biomechanical	N/A	> BBS
Labruyere & van Hedel.[72]	> to investigate immediate and longitudinal effects of two interventions on balance (among other measures) in patients with chronic iSCI	Both	> COP distance measure	> BBS
Lee et al.,[73]	to investigate factors that influence quiet standing balance	Both	ure derived from COP: stability index and weight distri	> BBS
Lemay & Nadeau[74]	> to document the concurrent validity of the BBS with various walking parameters for an SCI population	Non-Biomechanical	N/A	> BBS
Lemay & Nadeau[75]	> to investigate the concurrent validity of the Smart Balance Master (SBM) tests for measuring static and dynamic standing-balance in individuals with AID D iSCI by assessing the level of association between the BBS, walking speed and SBM test > to identify the most valuable test of the SBM for SCI population > to verify whether SBM scores for paraplegia and tetraplegia differ	Both	> COG distance measure > COG area measure > other measures derived from COG: limits of stability and movement time	> BBS
Lemay, Duclos, Nadeau, Gagnon & Desrosiers[76]	> to characterize balance in individuals with and without an iSCI	Biomechanical	> Forces/Torques: Stabilizing and Destabilizing forces calculated from kinematic and kinetic data	N/A
Lemay, Duclos, Nadeau, & Gagnon[77]	> to compare and describe postural control during bipedal and single-support phases of gait initiation and termination in individuals with iSCI	Both	> Forces/Torques: Stabilizing and Destabilizing forces calculated from kinematic and kinetic data	> BBS
Lemay, Gagnon, Duclos, Grangeon, Gauthier, & Nadeau[78]	> Compare use of visual inputs to maintain standing posture between participants with SCI to AB participants > Quantify relationship between visual contribution to standing posture & a clinical balance scale	Both	> COP velocity measure > COP area measure > COP variability measure (RMS) > other measures derived from COP: Romberg ratios	> miniBESTest
Lemay, Gagnon, Nadeau, et al.[79]	> to quantify standing dynamic postural balance by comparing lab-based dynamic postural balance test and quasi-static postural stability tests individuals with iSCI and AB individuals	Biomechanical	> COP distance measure > COP velocity measure > COP area measure > COP variability measure (RMS)	N/A
Liechti et al.[80]	> to investigate changes in postural responses following galvanic vestibular stimulation	Biomechanical	> EMG > COP distance measure	N/A
Lin, K., et al.[81]	> to investigate the postural control in SCI subjects with stable stance and unstable stance followed by a rapid reach-and-grasp balance reaction	Biomechanical	> other measures derived from COP: COM -COP difference > EMG: normalized average root mean square per unit and onset times	N/A
Lorenz et al.[82]	> to evaluate progression of BBS (among other measures) in individuals with incomplete SCI receiving standardized locomotor training	Non-Biomechanical	N/A	> BBS
Lu, Lien, and Hsieh.[83]	to validate the Balance Computerized Adaptive Testing (Balance CAT) by testing its correlation with BBS and Barthel Index in long-term care facilities	Non-Biomechanical	N/A	> BBS > BalanceCAT
Lynch et al. [84]	> to test reliability of Functional Reach Test for assessing sitting balance in people with SCI	Non-Biomechanical	N/A	> FRT
Matjacic [85]	> to test a new apparatus that enables dynamic walking balance during walking on treadmill for improving balance in individuals with SCI	Non-Biomechanical	N/A	> BBS
Matsubara, Wu & Gordon [86]	> to quantify the metabolic energy demands of maintaining lateral stability during gait	Non-Biomechanical	N/A	> BBS
Middleton et al.[87]	> Evaluate the effect of the Walkabout device (medial linkage joint that attaches to KAFO) on "dynamic postural stability and regulatory postural control during standing"	Biomechanical	> COP distance measure	N/A

Mihelj & Munih [88]	> to evaluate posture control system performed in a simulation-based study and on a paraplegic patient	Biomechanical	> other COP/COM measure: COM in relation to ankle joint axis > Forces/Torques: GRF and joint torques	N/A
Milosevic et al.[89]	> to compare postural control of individuals with cervical SCI and able-bodied individuals; and > to investigate the effects of foot support and trunk fluctuations on postural control during sitting	Biomechanical	> COP distance measure > COP velocity measure > COP area measure > COP frequency measure	N/A
Moriello et al.[90]	> to compare effect of forward versus backward walking using body weight supported treadmill training on measures of balance (in addition to other measures)	Non-Biomechanical	N/A	> Tandem Stance Component of SPPB
Moriello et al.[91]	to document outcomes of a yoga program	Non-Biomechanical	N/A	> BBS > FRT
Musselman et al.[92]	> to determine the effectiveness of skill training in a small group of people with iSCI and to compare skill training with body-weight–supported treadmill training (BWSTT) in the same individuals, with BBS as one of the study outcomes	Non-Biomechanical	N/A	> BBS
Nataraj et al.[93]	> to use COM acceleration feedback for improving performance of a functional neuromuscular stimulation (FNS) control system to restore standing function	Biomechanical	other measures derived from COM: COM acceleration	N/A
Parkinson, Reed & Chaffin.[94]	> to study seated reaching behaviour of people with spinal cord injury	Biomechanical	> COP length data > other COP measure: trajectories	N/A
Pernot et al.[95]	> to assess the interrater reliability and validity of the test-table-test (TTT) by correlating it with balance perturbation tests and COP displacement measurements	Both	> COP distance measure	> Test Table Test
Potten et al.[96]	> to investigate dissimilarities in postural control strategies between the SCI and non-SCI subjects	Both	> COP distance measure > EMG: mean rectified activity	> FRT
RoopchandMartin & Bateman [97]	> To exlpore improvements in seated balance of two individuals with SCI using a boxing programme on the Nintendo Wii	Non-Biomechanical	N/A	> FRT
Saraf et al.[98]	> to study the relationship between daily stepping in ambulatory individuals with SCI and clinical walking performance measures, incuding static balance.	Non-Biomechanical	N/A	> BBS
Sayenko et al.[99]	> to evaluate the learning potential and performance improvements during the balance training > to determine improvements in static and dynamic stability after balance training	Biomechanical	> COP distance measure > COP velocity measure > COP area measure > COP variability measure (RMS) > other measures derived from COP: stability zones	N/A
Scivoletto et al.[100]	> to evaluate the effects of neurologic and non-neurologic factors on balance (and other parameters)	Non-Biomechanical	N/A	> BBS
Seelen et al.[101]	> to study postural muscle use during sitting balance in individuals with a complete thoracic SCI	Biomechanical	> COP distance measure > EMG: mean rectified EMG > others: reactiontime/movement time	N/A
Seelen et al.[102]	> Centre of pressure displacement was assessed to use as an indicator for sitting balance perturbation	Biomechanical	> COP distance measure > others: reactiontime/movement time	N/A
Seelen, Potten, Adam, Drukker, Spaans & Huson.[103]	> to investigate the time course of postural reorganization during active, clinical rehabilitation of thoracic SCI patients with different SCI levels.	Both	> others: reactiontime/movement time	> FRT
Seelen, Potten, Drukker, Reulen, & Pons.[104]	> to investigate changes in the sitting balance across the clinical rehabilitation process	Biomechanical	> COP distance measure > EMG: mean rectified activity	N/A
Serra-Ano et al.[105]	> to analyse the temporal and frequency domains of seated balance > to explore the centre of pressure (CoP) limits before experiencing a fall	Biomechanical	> COP distance measure > COP variability measure > COP frequency measure > other measures derived from COP: limits of stability	N/A
Shin & Sosnoff [106]	> Determine whether postural instability in sitting can be quantified with the "virtual time to contact (VTC) analysis of seated postural control"	Biomechanical	> COP velocity measure > COP area measure > COP variability measure (RMS) > other measures derived from COP: instability indexes and virtual time to contact functional boundary	N/A
Shirado et al.[107]	> to evaluate and compare the ability to maintain the sitting posture between SCI and AB > to introduce a method to assess sitting posture	Biomechanical	> COP distance measure > other measures derived from COP: pattern of trace of the COP	N/A
Sprigle et al.[108]	to study the effect of 3 cusion types on pelvis and trunk control and upper extremity reach	Both	> Joint angles: pelvic and trunk angle > Reaching distance	> FRT
Sprigle et al.[109]	> To validate 3 clinical measures of postural stability (functional reach, reach area, bilateral reach) against performance of ADL tasks	Non-Biomechanical	N/A	> FRT
Srisim, Amatachaya & Saengsuwan.[110]	> to compare the utility of a balance measure (among other functional measures) to predict risk of multiple falls (fall !2 times) in individuals with SCI	Non-Biomechanical	N/A	> BBS > FRT
Stevens et al.[111]	> to document effects of underwater treadmill training on balance (in addition to leg strength and walking performance)	Non-Biomechanical	N/A	> BBS
Tamburella et al. [112]	> Evaluate the effectiveness of visual biofeedback task-specific balance training (vBFB) to improve balance and gait in comparison to conventional overground rehabilitation	Both	> COP distance measure > COP velocity measure > COP area measure > Gait Variables: speed, cadence, stride length, stance phase, double-support time)	> BBS
Tamburella, Scivoletto & Molinari. [113]	> to analyze the effects of KinesioTaping treatment on spasticity, balance and gait.	Both	> COP distance measure > COP velocity measure > COP area measure	> BBS
Tamburella, Scivoletto, Iosa, & Molinari. [114]	> to analyze the reliability, validity, and responsiveness of COP parameters to assess balance in individuals with iSCI	Both	> COP distance measure > COP velocity measure > COP area measure	> BBS > Tinetti Scale
Thigpen et al. [115]	> to investigate anticipatory and reactive balance responses in individuals with iSCI	Biomechanical	> EMG: mean amplitude and onset latencies	N/A
Tokita et al. [116]	> to analyze body sway in standing posture	Biomechanical	> COG distance measure > COG frequency measure	N/A
Triolo et al. [117]	> to evaluate and quantify the effects of activating the paralyzed hip and trunk musculature with FES on the sitting posture, stability and functional capacities of a single-subject with C4 AIS A tetraplegia	Biomechanical	> Reaching distance > Forces/Torques: resistance to externally applied disturbances	N/A
Triolo et al. [118]	> Determine whether electrical stimulation to hip & trunk muscles improves seated posture and reach	Biomechanical	> Joint angles: trunk angle and pelvic tilt > Reaching distance: bimanual relative (elbow joint) and absolute (elbow joint and trunk) reach > Forces/Torques: isokinetic forces exerted by the upper extremities in a simulated rowing task	N/A
Tsang et al. [119]	> to investigate the effects of sitting Tai Chi on dynamic sitting balance control	Biomechanical	> COP distance measure > other measures derived from COP: directional control of COP and reaction time	N/A
Vilchis-Aranguren et al. [120]	to evaluate the effects of using the INR cushion on trunk control (along with other measures)	Non-Biomechanical	N/A	> Ability to maintain while reacting to external perturbation:
Villiger et al. [121]	> to correlate improvements in training improvement-induced structural brain plasticity in chronic iSCI patients using longitudinal MRI with improvements in balance measures (in addition to other measures)	Non-Biomechanical	N/A	> BBS
Wall et al. [122]	to assess the effects of nintendo wii fit training on balance (along with other measures)	Non-Biomechanical	N/A	> FRT
Wannapakhe et al. [123]	> to evaluate changes in balance ability in partcipants with SCI who fell and those who did not fall during the 6-month period after discharge	Non-Biomechanical	N/A	> BBS
Wirz, Muller, & Bastiaenen. [124].	> to determine association between the BBS and number of falls experienced over a period of 5 months > to determine association between the BBS and other measures of mobility (including WISCI, gait speed, SCIM), motor scores, and the Falls Efficacy Scale - International Version (FES I) > to explore cut-off scores on the BBS for discriminating people with a risk of falling > to assess interobserver reliability of the BBS	Non-Biomechanical	N/A	> BBS
Wu et al. [125]	> to determine improvements in balance (among other measures) in individuals with iSCI with robotic resistance training	Both	> Gait variables: single/double leg support	> BBS
Wydenkeller et al. [126]	> to investigate influence of vestibular spinal responses to postural instability in individuals with iSCI	Biomechanical	> COP distance measure > EMG	N/A
Yu et al. [127]	> to analyze standing balance (changes of COP, joint moment, joint angle, and muscle activities during quiet stance) with and without arm support in patients with incomplete SCI	Biomechanical	> COP distance measure > COP area measure > Joint angles/torques/moments > EMG	N/A

APPENDIX F. Supplementary Table S3

Citation	Was the assessment prospective or retrospective	Subject Definition (Adequate, Partial or Inadequate details)	Inclusion Criteria (Stated, Limited or Not Stated)	Sampling method (Convenience, Community-based, Population-based, or not stated)	Validity of non-biomech measures in individuals with SCI, stated/tested - type? (Stated/tested (type of validity), Not stated/tested)	Reliability of non-biomech measures in individuals with SCI, stated/tested - type?? (Stated/tested (type of reliability), Not stated/tested)
Adegoke et al.[1]	Prospective	Partial	Stated	Convenience	FRT Tested (discriminative - did not differ between different groups based on level of injury)	FRT Stated (test-retest) Tested (test-retest)
Alexeeva et al.[2]	Prospective	Adequate	Stated	Population based	Tinetti Scale: Not stated/tested	Tinetti Scale: Not stated/tested
Allison & Singer [3]	Prospective	Adequate	Not stated	Not stated	N/A	N/A
Altmann et al.[4]	Prospective	Inadequate	Limited	Convenience	N/A	N/A
Amatachaya, Pramodhyakul & Srisim [5]	Prospective	Adequate	Stated	Convenience	Ability to Cross Obstacles: Not stated/tested	Ability to Cross Obstacles: Not stated/tested
Amatachaya, Pramodhyakul, Wattanapan, & Eungpinichpong.[6]	Prospective	Adequate	Stated	Convenience	Ability to Cross Obstacles: Not stated/tested	Ability to Cross Obstacles: Not stated/tested
Arazpour et al.[7]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Ardolino et al.[8]	Prospective	Partial	Stated	Convenience	ABLE: Tested (content, construct, discriminant)	ABLE: Tested (internal consistency)
Audu & Triolo.[9]	Prospective	Partial	Not Stated	Not Stated	N/A	N/A
Audu et al.[10]	Prospective	Adequate	Not Stated	Not Stated	N/A	N/A
Baardman et al.[11]	Prospective	Adequate	Stated	Not stated	N/A	N/A
Bahrami et al.[12]	Prospective	Partial	Not stated	Not stated	N/A	N/A
Barthelemy et al.[13]	Prospective	Adequate	Limited	Not stated	BBS: Stated (concurrent)	BBS: Not stated/tested
Barthelemy, et al.,[14]	Prospective	Adequate	Not Stated	Not stated	BBS: Stated (concurrent)	BBS: Stated (interrater)
Behrman et al.[15]	Prospective	Adequate	Limited	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Benedetti et al.[16]	Prospective	Partial	Limited	Convenience	N/A	N/A
Bernard et al.[17]	Prospective	Partial	Limited	Convenience	N/A	N/A
Betker et al.[18]	Prospective	Partial	Not stated	Not stated	CTSIB: Not stated/tested	CTSIB: Not stated/tested
Bishop et al.[19]	Prospective	Adequate	Not stated	Not stated	BBS: Not stated/tested	BBS: Not stated/tested
Bjerkefors et al.[20]	Prospective	Adequate	Stated	Not stated	N/A	N/A
Bjerkefors et al.[21]	Prospective	Adequate	Not stated	Convenience	N/A	N/A
Bolin et al.[22]	Prospective	Adequate	Limited	Convenience	FRT: Not stated/tested	FRT: Not stated/tested
BoswellRuys et al.[23]	Prospective	Partial	Stated	Community-based	FRT: stated (construct and discriminative) Timed Dressing/Undressing: Not stated/tested	FRT related: Stated (test-retest) Timed Dressing/Undressing: Not stated/tested
BoswellRuys, et al.[24]	Prospective	Adequate	Limited	Convenience	FRT Tested (construct and discriminative) Timed Dressing/Undressing: Not stated/tested	FRT Stated (test-retest) Tested (test-rest) Timed Dressing/Undressing: Not stated/tested
Braz et al.[25]	Prospective	Adequate	Not stated	Not stated	N/A	N/A
Buehner et al.[26]	Prospective	Adequate	Limited	Convenience	BBS: Stated (concurrent)	BBS: Stated (interrater)
Chaffin et al.[27]	Prospective	Partial	Not stated	Not stated	N/A	N/A
Chan et al.,[28]	Retrospective	Adequate	Stated	Convenience	BBS: Stated (concurrent) CB&M Tested (convergent)	BBS: Not stated/tested CB&M: Tested (internal consistency)
Chen et al.[29]	Prospective	Adequate	Limited	Convenience	Timed Dressing/Undressing: Not stated/tested	Timed Dressing/Undressing: Not stated/tested
Chisholm et al.[30]	Prospective	Adequate	Not stated	Not stated	Timed Standing: Not stated/tested	Timed Standing: Not stated/tested
Cybulski & Jaeger[31]	Prospective	Partial	Limited	Not stated	N/A	N/A
Datta et al.[32]	Prospective	Adequate	Stated	Convenience	BBS: Stated (face validity)	BBS: Not stated/tested
Datta et al.[33]	Prospective	Adequate	Limited	Convenience	BBS: Stated (concurrent; predictive - not good) Tested (construct)	BBS: Stated (interrater reliability)
Day et al. [34]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested DGI: Not stated/tested	BBS: Not stated/tested DGI: Not stated/tested

de Abreu et al.[35]	Prospective	Partial	Stated	Not stated	N/A	N/A
Desrosiers, Nadeau, & Duclos.[36]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Ditunno et al.[37]	Prospective	Partial	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Field-Fote & Ray.[38]	Prospective	Adequate	Stated	Convenience	FRT Not stated/tested	FRT Stated: yes (test-retest in motor complete injuries) Tested (test-retest in motor incomplete injuries)
Findlay et al.[39]	Prospective	Inadequate	Stated	Convenience	Romberg's Sign: Not stated/tested	Romberg's Sign: Not stated/tested
Forrest et al.[40]	Prospective	Adequate	Stated	Convenience	BBS: Stated (concurrent) FRT:	BBS: Stated (interrater) FRT:
Foster et al.[41]	Prospective	Adequate	Not stated	Not stated	BBS: Stated (concurrent)	BBS: Stated (interrater)
Freivogel et al.[42]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Fritz, S. et al.[43]	Prospective	Partial	Stated	Convenience	BBS: Stated (concurrent) DGI: Stated (validaty has not been established)	BBS Stated (interrater) DGI Not stated/tested
Fritz, S., et al.[44]	Prospective	Partial	Stated	Community-based	BBS: Not stated/tested DGI: Not stated/tested	BBS: Not stated/tested DGI: Not stated/tested
Gagnon et al.[45]	Prospective	Adequate	Stated	Not stated	N/A	N/A
Gao et al.[46]	Prospective	Adequate	Stated	Not Stated	N/A	N/A
Gauthier et al.[47]	Prospective	Partial	Stated	Convenience	N/A	N/A
Gauthier et al.[48]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Gillette et al.[49]	Prospective	Partial	Not stated	Not stated	N/A	N/A
Gillette et al.[50]	Prospective	Partial	Not stated	Not stated	N/A	N/A
Gorgey et al.[51]	Prospective	Partial	Not stated	Not stated	BBS: Not stated/tested	BBS: Not stated/tested
Granat et al.[52]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Grangeon et al.[53]	Prospective	Partial	Limited	Not stated	N/A	N/A
Grigorenko et al.[54]	Prospective	Adequate	Limited	Convenience	N/A	N/A
Harel et al.[55]	Prospective	Adequate	Limited	Not stated	BBS: Stated (concurrent) FRT: Not stated/tested	BBS: Stated (type not mentioned) FRT Not stated/tested
Harkema et al.[56]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Harvey et al.[57]	Prospective	Adequate	Stated	Convenience	FRT: Stated (construct and discriminative)	FRT Stated (test-retest)
Janssen_Potten et al.[58]	Prospective	Partial	Limited	Not stated	FRT: Not stated/tested	FRT: Not stated/tested
Janssen-Potten et al.[59]	Prospective	Partial	Limited	Not stated	FRT: Not stated/tested	FRT: Not stated/tested
Janssen-Potten et al.[60]	Prospective	Partial	Limited	Not stated	FRT: Not stated/tested	FRT: Stated (test-retest reliability)
John, L. et al.[61]	Prospective	Partial	Stated	Convenience	N/A	N/A
Jorgensen et al.[62]	Prospective	Adequate	Stated	Convenience	MAS and SBS: Tested (convergent: validity found to be variable and not so good)	MAS and SBS: Tested (interrater reliability)
Kamper, Barin et al.[63]	Prospective	Adequate	Limited	Not stated	N/A	N/A
Kamper, Parnianpour et al.[64]	Prospective	Adequate	Limited	Not stated	N/A	N/A
Karatas et al.[65]	Prospective	Partial	Limited	Convenience	N/A	N/A
Karcnik & Kralj [66]	Prospective	Partial	Not Stated	Not stated	N/A	N/A
Karimi et al.[67]	Prospective	Partial	Limited	Not stated	N/A	N/A
Kim et al.,[68]	Prospective	Adequate	Limited	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Kim, Chung, & Shin. [69]	Prospective	Partial	Stated	Convenience	FRT: Not stated/tested	FRT: Stated (test-retest)
Kizony et al.[70]	Prospective	Adequate	Not stated	Convenience	FRT: Not stated/tested	FRT: Not stated/tested
Kubota et al.[71]	Prospective	Partial	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Labruyere & van Hedel.[72]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Lee et al.,[73]	Prospective	Partial	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested

Lemay & Nadeau[74]	Prospective	Partial	Stated	Convenience	BBS: Tested (concurrent; discriminative: no significant difference between individuals with paraplegia and tetraplegia)	BBS: Not stated/tested
Lemay & Nadeau[75]	Prospective	Adequate	Stated	Convenience	BBS: Stated (convergent and discriminative)	BBS: Not stated/tested
Lemay, Duclos, Nadeau, Gagnon & Desrosiers[76]	Prospective	Partial	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Lemay, Duclos, Nadeau, & Gagnon[77]	Prospective	Partial	Stated	Convenience	N/A	N/A
Lemay, Gagnon, Duclos, Grangeon, Gauthier, & Nadeau[78]	Prospective	Partial	Stated	Not stated	miniBESTest: Not stated/tested	miniBESTest: Not stated/tested
Lemay, Gagnon, Nadeau, et al.[79]	Prospective	Partial	Stated	Convenience	N/A	N/A
Liechti et al.[80]	Prospective	Adequate	Stated	Not stated	N/A	N/A
Lin, K., et al.[81]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Lorenz et al.[82]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Lu, Lien, and Hsieh.[83]	Prospective	Inadequate	Limited	Community-based	BBS: Not stated/tested BalanceCAT Tested in long term care residents including SCI (concurrent and discriminative)	BBS: Not stated/tested Balance CAT: Tested in long term care residents including SCI (interrater)
Lynch et al. [84]	Prospective	Partial	Stated	Convenience	FRT Tested (face validity - subjectively; and discriminative)	FRT: Tested (test-retest reliability)
Matjacic [85]	Prospective	Adequate	Not Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Matsubara, Wu & Gordon [86]	Prospective	Adequate	Stated	Not Stated	BBS: Not stated/tested	BBS: Not stated/tested
Middleton et al.[87]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Mihelj & Munih [88]	Prospective	Inadequate	Not stated	Not stated	N/A	N/A
Milosevic et al.[89]	Prospective	Adequate	Stated	Not Stated	N/A	N/A
Moriello et al.[90]	Prospective	Adequate	Not stated	Not stated	Tandem Stance Component of SPPB: Stated: Overall SPPB (concurrent)	SPPB Not stated/tested
Moriello et al.[91]	Prospective	Adequate	Not stated	Not stated	BBS: Stated (concurrent) FRT : used for hams flexibility	BBS: Stated (interrater) FRT: used for hams flexibility
Musselman et al.[92]	Prospective	Adequate	Limited	Community-based	BBS: Stated (type not mentioned)	BBS: Not stated/tested
Nataraj et al.[93]	Prospective	Partial	Not stated	Not stated	N/A	N/A
Parkinson, Reed & Chaffin.[94]	Prospective	Inadequate	Limited	Not stated	N/A	N/A
Pernot et al.[95]	Prospective	Adequate	Stated	Community-based	Test Table Test: Tested (criterion)	Test Table Test: Tested (interrrater reliability)
Potten et al.[96]	Prospective	Partial	Limited	Not stated	FRT: Not stated/tested	FRT: Not stated/tested
RoopchandMartin & Bateman [97]	Prospective	Adequate	Stated	Convenience	FRT: Not stated/tested	FRT: Stated (test-retest)
Saraf et al.[98]	Prospective	Partial	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Sayenko et al.[99]	Prospective	Adequate	Limited	Not stated	N/A	N/A
Scivoletto et al.[100]	Prospective	Adequate	Stated	Not stated	BBS: Not stated/tested	BBS: Not stated/tested
Seelen et al.[101]	Prospective	Partial	Limited	Not stated	N/A	N/A
Seelen et al.[102]	Prospective	Partial	Stated	Not stated	N/A	N/A
Seelen, Potten, Adam, Drukker, Spaans & Huson.[103]	Prospective	Adequate	Stated	Convenience	FRT: Not stated/tested	FRT: Not stated/tested
Seelen, Potten, Drukker, Reulen, & Pons.[104]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Serra-Ano et al.[105]	Prospective	Adequate	Stated	Not stated	N/A	N/A
Shin & Sosnoff [106]	Prospective	Partial	Not stated	Convenience	N/A	N/A
Shirado et al.[107]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Sprigle et al.[108]	Prospective	Partial	Stated	Not stated	FRT: Not stated/tested	FRT: Tested (test-retest reliability)
Sprigle et al.[109]	Prospective	Partial	Stated	Convenience	FRT Tested (convergent and discriminative)	FRT Stated: (test-retest reliability - from a test chair) Tested: (test-retestest from subject's own chair)
Srisim, Amatachaya & Saengsuwan.[110]	Prospective	Adequate	Stated	Convenience	BBS: Stated (concurrent) Tested (predictive - could not differentiate between multiple fallers and non-multiple fallers) FRT: Tested (predictive)	BBS: Stated (interrater reliability) Tested (interrater reliability) FRT: Tested (interrater)
Stevens et al.[111]	Prospective	Adequate	Stated	Community-based	BBS: Stated (concurrent)	BBS: Not stated/tested
Tamburella et al. [112]	Mixed prospective/retrospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Tamburella, Scivoletto & Molinari. [113]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested

Tamburella, Scivoletto, Iosa, & Molinari. [114]	Prospective	Adequate	Stated	Not Stated	BBS: Not stated/tested Tinetti Scale - equilibrium and not locomotor: Not stated/tested	BBS: Tested (intra-rater) Tinetti: Tested (intra-rater)
Thigpen et al. [115]	Prospective	Partial	Stated	Convenience	N/A	N/A
Tokita et al. [116]	Prospective	Inadequate	Not stated	Not stated	N/A	N/A
Triolo et al. [117]	Prospective	Adequate	Not stated	Not stated	FRT Not stated/tested	FRT: Not stated/tested
Triolo et al. [118]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Tsang et al. [119]	Prospective	Adequate	Stated	Convenience	N/A	N/A
Vilchis-Aranguren et al. [120]	Prospective	Partial	stated	Convenience	Ability to maintain while reacting to external perturbation: Not stated/tested	Ability to maintain while reacting to external perturbation: Not stated/tested
Villiger et al. [121]	Prospective	Adequate	Stated	Convenience	BBS: Not stated/tested	BBS: Not stated/tested
Wall et al. [122]	Prospective	Adequate	Stated	Convenience	FRT: Not stated/tested	FRT: Not stated/tested
Wannapakhe et al. [123]	Prospective	Partial	Stated	Convenience	BBS: Stated (concurrent)	BBS: Stated (interrater)
Wirz, Muller, & Bastiaenen. [124].	Mixed prospective/retrospective	Adequate	Limited	Convenience	BBS: Stated: yes, type not mentioned Tested (concurrent ; predictive: not established)	BBS: Tested (interrater)
Wu et al. [125]	Prospective	Adequate	Stated	Not stated	BBS: Not stated/tested	BBS: Not stated/tested
Wydenkeller et al. [126]	Prospective	Partial	Limited	Not stated	N/A	N/A
Yu et al. [127]	Prospective	Adequate	Stated	Convenience	N/A	N/A

APPENDIX G. Supplementary Table S4

Name of the Measure	Time Taken (3 = less than 10 minutes 2 = 10-30 minutes 1 = 30-60 minutes 0 = >1 hour)	Cost (3 = less than 100 pounds (CAD 172.8) 2 = 100-500 pounds (CAD 172.8 - 864.01) 1 = 500-1000 pounds (CAD 864.01 - 1728) 0 = >1000 pounds(> CAD 1728))	Measurement Tool need Specialist Equipment and Training to Use? Time Taken (2 = no 1 = yes, but simple and clinically feasible 0 = yes, and not clinically feasible/unknown)	Portability (2 = yes easily (can go in pocket) 1 = yes, in a briefcase or trolley, or large piece (e.g. stairs/chair) typically found in clinical environment 0 = no or very difficult)	Total
Groupings By Biomechanical Construct					
COP/COM related variables (motion capture/force plates)	0	0	0	0	0
EMG	0	0	0	1	1
Forces/Torques (motion capture/forceplate/isokinetic)	1	0	0	1	2
Joint Angles (motion capture)	0	0	0	0	0
Instrumented Reaching Distance (vicon)	0	0	0	0	0
Instrumented Gait Variables (motion capture/instrumented walkway)	0	0	0	0	0
Reaction/Movement Times (using specialized equipment)	0	0	0	0	0
Others					0
Fall Threshold (using perturbation platform)	0	0	0	0	0
Trunk Stiffness (using a specialized sitting surface - with perturbation)	0	0	0	0	0
Linear Momentum (motion capture)	0	0	0	0	0
Dampning Factor	0	0	0	0	0
Balance Scales					
Berg Balance Scale	2	3	2	1	8
Functional Reach Test	3	3	2	2	10
Dynamic Gait Index	2	3	2	1	8
Tinetti	2	3	2	2	9
Mini-BESTest	2	3	2	1	8
Activity Based Level Evaluation	1	3	2	2	8
Clinical Test of Sensory Organization and Balance	2	3	2	2	9
Test Table Test	3	3	2	2	10
Motor Assessment Scale - balanced sitting component	3	3	2	2	10
Sitting Balance Score	3	3	2	2	10
Romberg	3	3	2	2	10
Community Balance and Mobility	2	3	2	1	8
BalanceCAT	3	3	2	2	10
Body Sway using Lord Sway Meter	3	3	1	1	8
Standardized Obstacle Clearing Tests	3	3	2	1	9
T-shirt Test	3	3	2	2	10
Timed Standing	3	3	2	2	10
Timed Tandem Stance	3	3	2	2	10
Seated Reaction to Perturbation	3	3	2	2	10

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