The integration of vision and proprioception for obstacle crossing in people with motor-incomplete spinal cord injury

by

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Abstract

Background: In people with motor-incomplete spinal cord injury (m-iSCI), the ability to perform skilled walking tasks (e.g. obstacle crossing) is an essential component of functional mobility. Sensorimotor integration of visual and proprioceptive inputs, alongside indicators of functional ambulation (i.e. self-efficacy) is important for successful obstacle crossing. Thus, the overall objective was to understand how motor and sensory (specifically proprioception) deficits in people with m-iSCI affect obstacle-crossing strategies.

Methods: Nine individuals with m-iSCI and 10 able-bodied controls were asked to step over an obstacle scaled to their motor abilities under full and obstructed vision conditions. An eye tracker was used to determine gaze behavior, motion capture analysis was used to determine toe kinematics relative to the obstacle, and electrogoniometers were used to determine peak ankle, hip and knee (dorsi)flexion angles during obstacle crossing. In subjects with m-iSCI, questionnaires were used to determine balance and ambulatory self-efficacy. Lower limb proprioceptive sense was assessed using a hip and knee joint position-matching task using the Lokomat and customized software controls. **Results:** Lower limb proprioceptive sense was impaired and varied across subjects with m-iSCI. m-iSCI subjects tended to glance at the obstacle more frequently as they approached it and with shorter gaze durations compared to controls. Decreased selfefficacy and impaired proprioceptive sense may have contributed to these differences in gaze behavior. Obstruction of the lower visual field led to appropriate modulation of lead and trail horizontal distance, however toe clearance height in m-iSCI subjects was increased to a greater extent than controls. An emerging relationship was observed

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between proprioceptive sense and toe clearance height, in particular for the trail limb. miSCI subjects increased peak knee flexion to a greater extent than controls when vision was obstructed. All other changes in joint kinematics were similar across groups.

Conclusion: The results of this study indicate that people with m-iSCI rely more heavily on vision to cross obstacles and show impairments in the key gait parameters required for successful obstacle crossing. Our data suggest that proprioceptive deficits also need to be considered in rehabilitation programs aimed at improving functional mobility in individuals with m-iSCI.

Preface

All data contained in this thesis were collected by Raza Naseem Malik at the Human Locomotion Research Laboratory within the the Blusson Spinal Cord Centre, Vancouver, BC. Methodologies were reviewed and approved by the UBC Clinical Research Ethics Board (#H10-02588)

The study contained in this thesis was not submitted for publication at the time of thesis submission.

I was the lead investigator on the project, responsible for concept development, data collection and analysis, and manuscript composition. Dr. J Timothy Inglis and Dr. Janice J. Eng were involved in concept development. Dr. Tania Lam was the supervisory author on the project and was involved in concept formation and thesis revisions.

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Introduction

Over 85,000 people are living with spinal cord injury (SCI) in Canada, with an estimated 3,000 new cases per year (Noonan et al., 2012). The incidence and prevalence of SCI has continued to increase over the past decade, meaning more people are being faced with the overwhelming consequences of SCI (DeVivo, 2012; Furlan et al., 2012; 2013). SCI usually results in paralysis due to direct sensorimotor impairments (Raineteau and Schwab, 2001; Dietz and Fouad, 2013). The paralysis and resulting deficits in mobility leads to profound secondary complications due to pressure sores and neuropathic pain, as well as autonomic, respiratory and immunological dysfunction (McKinley et al., 1999; Krassioukov et al., 2003). Therefore, rehabilitation is critical for helping people with SCI attain their maximum level of mobility, including the recovery of functional walking ability when possible, and overall quality of life.

SCI can result from both traumatic and non-traumatic causes. Traumatic injuries result from external causes such as motor vehicle accidents, sports injuries, falls or violence (Farry and Baxter, 2010; Furlan et al., 2012; Noonan et al., 2012). Non-traumatic causes include arthritis of the vertebrae, tumors, infections, or other illnesses (Farry and Baxter, 2010; Noonan et al., 2012). The resulting degree of impairment is contingent on the level and severity (Farry and Baxter, 2010). The level of injury determines the amount of paralysis as all fibers at and below the injury are affected. Injuries to the cervical cord lead to tetraplegia while thoracic, lumbar, and sacral cord injuries lead to paraplegia. The extent of motor and sensory deficits also depends on the completeness of the injury. In complete injuries, there is little sparing of the motor and

sensory fibers below the lesion, while in an incomplete spinal cord injury there is some preservation of these fibers, meaning residual sensori-motor function remains below the lesion (Waters et al., 1991; Raineteau and Schwab, 2001; Farry and Baxter, 2010; Dietz and Fouad, 2013). Spared fibers along descending motor pathways make the recovery of walking a feasible goal for people with motor-incomplete SCI (m-iSCI), while the prospects for the restoration of function ambulation is less favorable for people with complete injuries (Waters et al., 1991; Farry and Baxter, 2010).

The level and severity of a person's injury is a key factor in determining their health related goals. For tetraplegics the top health priority is to regain upper extremity function alongside bowel/bladder function (Anderson, 2004; Simpson et al., 2012). On the other hand, a top health priority for paraplegics is to regain functional ambulation, in addition to regaining sexual and bowel/bladder function (Brown-Triolo et al., 2002; Ditunno et al., 2008; Simpson et al., 2012). Other authors have also highlighted the importance of the recovery of walking for people with SCI (Estores, 2003; Donnelly et al., 2004; Ditunno et al., 2008) Functional ambulation refers to "the ability to walk, with or without the aid of appropriate assistive devices (such as prostheses, orthoses, canes, or walkers), safely and sufficiently to carry out mobility-related activates of daily living" (Lam et al., 2007). A large body of literature has used various locomotor training interventions based on the concept of activity dependent plasticity to aid in the recovery of functional ambulation after SCI (Barbeau and Fung, 2001; Edgerton and Roy, 2002; Harkema et al., 2012). Repetitive and intensive gait practice provides task-specific sensory feedback to the spared spinal networks, in an attempt to activate the spared motor pathways (Barbeau and Fung, 2001; Edgerton and Roy, 2002). Essentially, such

therapeutic strategies rely on the concept that with enough training the spinal cord can reorganize its circuitry and re-learn movements such as walking.

Very few studies to-date have examined the effects of locomotor training on functional skills that are necessary for everyday tasks, such as walking over different surfaces, carrying items while walking, and crossing obstacles (Musselman and Yang, 2007; Musselman et al., 2011; Musselman and Yang, 2013). Rather, the focus has been on measuring changes in overground walking speed and endurance, measures that are typically tested in an open gym space on a level, flat floor with no obstructions, which is a rare setting in everyday life (Lam et al., 2007; Wessels et al., 2010; Harkema et al., 2012; Morawietz and Moffat, 2013). Insights into a person's ability to functionally ambulate are likely a combination of the capability of completing skilled walking tasks alongside standard measures of walking speed and endurance.

The multi-segmental control of obstacle crossing

The seeming ease and automaticity of our ability to walk and adapt to the environment belies the complex mechanical interactions underlying the control of locomotion. Human gait is a repetitive movement that can be broken down into individual cycles (Perry, 1992). The goal of each cycle is to progress the limb upward and forward in a safe and efficient manner towards the desired target (Perry, 1992). To do this, the swing and stance limbs work together to generate and absorb power by counteracting and utilizing inter-segmental dynamics (Winter and Robertson, 1978; Patla and Prentice, 1995; Zernicke and Smith, 1996).

The stance limb is important for keeping the body upright and activating the appropriate muscles to achieve optimal swing clearance (Winter, 1980; Perry, 1992). The initial part of stance begins at heel contact and is dominated by active knee extensor activity to absorb the energy produced in late swing (Winter and Robertson, 1978; Winter, 1980; 1983; Perry, 1992; McFadyen et al., 1993; Zernicke and Smith, 1996). The second half of stance is responsible for the initiation of the swing phase (limb progression and elevation) (Winter, 1980; Zernicke and Smith, 1996). There are two key moments in the second half of stance; the push off and toe off phases. The push off phase is the single largest work phase in the gait cycle, as the biarticular gastrocnemius muscle generates power by actively contracting to produce plantar-flexor and knee flexor torques (Winter and Robertson, 1978; Winter, 1980; 1983; Perry, 1992). As the stance limb progresses to toe-off, a small knee extensor moment is created followed by hip flexor recruitment to elevate the limb and move it forward (Winter and Robertson, 1978; McFadyen et al., 1993). During obstacle crossing the basic locomotor pattern at toe-off shifts from a hip flexor to a knee flexor strategy (McFadyen et al., 1993; McFadyen and Carnahan, 1997). The normal knee-extensor and hip-flexor moments in the second half of stance are decreased and the generation of a new knee flexor moment is observed (McFadyen et al., 1993; McFadyen and Carnahan, 1997).

The control of swing limb trajectory is critical for foot clearance to avoid tripping and falling. The propulsion of the limb upward and forward from the active contractions in late stance generates motion dependent torques, which are moments generated around a joint due to the movements occurring at other joints (Patla and Prentice, 1995). During swing, motion-dependent torques facilitate limb trajectory while minimizing energy costs

(Winter and Robertson, 1978; Hoy and Zernicke, 1985; Winter, 1992; Patla and Prentice, 1995; Zernicke and Smith, 1996; Shemmell et al., 2007). The first half of swing is important for achieving adequate toe clearance and is mainly achieved by flexion of the hip, knee and ankle joints. During obstacle crossing, knee flexion of the swing limb is produced by an active muscle contraction, while swing hip and ankle flexion are achieved via motion dependent torques (Patla and Prentice, 1995). Specifically, shank angular velocity plays a critical role in facilitating ankle dorsiflexion and leg angular velocity and knee joint acceleration play a critical role in hip flexion (Patla and Prentice, 1995). Once adequate limb elevation is achieved, the rectus femoris contracts to produce a slight extensor torque to counterbalance the initial flexor torque and control limb trajectory height (Winter and Robertson, 1978; Winter, 1983; McFadyen and Carnahan, 1997). The motion dependent torques then help create an overall net extensor torque as the limb begins to move back towards the ground (Patla and Prentice, 1995; Zernicke and Smith, 1996). The hamstrings (knee flexors) then become active to slow down the limb and prepare for heel contact (Winter and Robertson, 1978; Winter, 1983; McFadyen and Carnahan, 1997). Just prior to heel contact the velocity of the limb is close to zero as power is absorbed in the initial part of stance (Winter and Robertson, 1978; Winter, 1983; Zernicke and Smith, 1996).

Foot trajectory height is influenced by both stance and swing limbs. Foot-floor clearance is an end-point control task under the influence of a seven-segment chain across both limbs, beginning with the stance foot moving up to the hip across the pelvis and ending with the swing foot (Winter, 1992). Sensitivity analysis has shown that slight changes in any of the seven joints can affect the end-point position of the limb,

particularly that in the hip during stance or the knee during swing. Angular changes of as little as 0.86 degrees in the stance hip angle or 1.25 degrees in the swing knee leads to significant changes in toe-trajectory height. This is in accordance with findings that swing limb elevation during obstacle crossing is mainly achieved by hip translational energy of the stance limb and knee rotational energy of the swing limb (Winter, 1992; Patla and Prentice, 1995) During normal and adaptive gait the human body is able to take advantage of these linkages to minimize energy costs by utilizing inter-segmental dynamics (Winter, 1992; Patla and Prentice, 1995; Zernicke and Smith, 1996).

The control of lower limb dynamics has not yet been analyzed in spinal cord injury, however analysis of lower limb kinematics during obstacle crossing gives some insight into the effects of SCI on obstacle crossing. There is limited lower limb kinematic data that shows that during obstacle crossing, persons with m-iSCI tend to rely on increased knee flexion, whereas able-bodied persons increase both knee and hip flexion when stepping over an obstacle (Ladouceur et al., 2003). Interestingly, it has been shown that the increase in hip flexion during obstacle crossing is achieved through intersegmental dynamics in able-bodied individuals (McFadyen and Winter, 1991; Patla and Prentice, 1995). Previous work has also shown that the requirement for increased hip flexion for obstacle crossing is reduced when the limb is positioned closer behind the obstacle (McFadyen et al., 1993). It is possible that the sensorimotor deficits in individuals with m-iSCI result in difficulties in deploying inter-segmental control strategies during locomotion, thereby limiting obstacle-crossing strategies.

In the absence of vision, the control of inter-segmental dynamics becomes more dependent on the proprioceptive system (Sainburg et al., 1993). The effects of visual

restriction on obstacle crossing have been highlighted in a study that compared persons with m-iSCI with able-bodied controls on a treadmill-based precision obstacle crossing task (crossing an oncoming obstacle with minimal toe clearance) (van Hedel et al., 2005). Acoustic feedback was given to signal the arrival of the obstacle, and feedback was given about performance (toe clearance) after crossing the obstacle. With vision restricted, the authors reasoned that acoustic and tactile (obstacle hits) information must be integrated with lower limb proprioception to drive accurate lead toe elevation (van Hedel et al., 2005). Indeed, in the restricted vision conditions, persons with m-iSCI hit the obstacle significantly more often compared to the controls. Although the controls did hit the obstacle more often when vision was restricted, the number of hits was not significantly different compared to their full vision trials. Intriguingly, of the three m-iSCI subjects who hit the obstacle most often, two of them had the most abnormal somatosensory evoked potentials (van Hedel et al., 2005). It is possible that in the absence of vision, persons with greater somatosensory impairments had more difficulty integrating the acoustic and tactile feedback with an estimation of limb position, which exacerbated the chance of contact with the obstacle. Because of the established role of proprioception in multi-joint movements (Sainburg et al., 1993; Bosco and Poppele, 1997; 2001) it is possible that proprioceptive deficits in persons with m-iSCI may lead to the abnormal control of inter-segmental dynamics.

Sensory Control of Obstacle Crossing

The motor command sent to the muscles in order to complete an obstacle-crossing task is under the influence of multiple sensory modalities. Two important sensory modalities in the control of obstacle-crossing are vision and proprioception. Vision plays

an important role in the identification of potential hazards, while also providing information about self-motion. Proprioception, on the other hand, plays a role in the control of inter-segmental dynamics and maintaining an internal representation of the body. The integration of these modalities, among others, has been speculated to play a critical role in the control of obstacle crossing (Lajoie and Drew, 2007; Marigold et al., 2011).

Vision is essential for identifying and initiating the appropriate gait modifications to a potential hazard (Patla, 1998; Marigold et al., 2011). When an obstacle (or any other hazard) is present in the walking path, vision is first used to identify and prime the system for an upcoming gait modification (Patla, 1998; Marigold et al., 2011). During the initial identification, visual information is used to extract the spatial (obstacle location, height and width) and temporal attributes (speed of the obstacle, if it is moving, and information about self motion) of the hazard (Marigold et al., 2011).

Limb state estimation relies on proprioceptive information, along with the efference copy of the motor command (Miall and Wolpert, 1996; Wolpert et al., 1998b; Desmurget and Grafton, 2000; Wolpert et al., 2000). Proprioceptive information provides knowledge of the limbs and body in space as well as information about self-motion (whether the limbs are moving or not, and the speed of movement). The information obtained from vision is integrated with proprioceptive information to generate a set of motor command (efference copy) has been proposed to play a role in predicting the future state of the limb via a forward model (Miall and Wolpert, 1996; Wolpert et al., 1998b; Desmurget and Grafton, 2000; Wolpert et al., 2000). When the efference copy is sent to

the forward model it is able to predict the sensory consequences of the movement. This information is then integrated with actual sensory feedback (from proprioceptors) to make on-line movement corrections and to update the forward model (Desmurget et al., 1999; Shadmehr and Krakauer, 2008). Evidence from animal and human neurophysiological studies indicate that the integration of obstacle location, self motion and a spatial estimation of limb position is critical for initiating the appropriate locomotor response to an obstacle. (Fig.1) (Marigold et al., 2011; Marigold and Drew, 2011)



Figure 1: The integration of vision and proprioception during obstacle crossing. Adapted from Marigold et al., 2011.

Proprioceptive Control of Limb Dynamics

The role of proprioception in human movement has predominantly been studied by assessing individuals with complete deafferentation (complete proprioceptive loss below the neck). These individuals provide a unique opportunity to understand the role of proprioception in movement control. The deficits seen in movement control when vision is not available to these individuals inform us of the potential role of proprioception in movement control.

Experimental results from deafferented subjects demonstrate that proprioception plays a crucial role in the control of multi-joint movements that rely on the precise control of inter-segmental dynamics (Sainburg et al., 1993; 1995). To illustrate the role of proprioception in controlling motion dependent torques, deafferented and able-bodied individuals were asked to pantomime a gesture similar to slicing a loaf of bread. To complete the task the hand first moves away from the body, approximately along the sagittal plane, reverses direction, and then moves back towards the body (Sainburg et al., 1993). This is a clever end-point control task (wrist path) as accuracy is dependent on the precise coordination between the shoulder and elbow. Motion capture analysis showed that in the absence of vision, able bodied individuals can complete this task with ease, maintaining a straight wrist path, while movement cycles were maintained within the same plane of movement (Sainburg et al., 1993). Conversely, deafferented subjects displayed curved wrist paths, while movement cycles were non-planar when they moved in the absence of vision. The spatial distortion of wrist path became obvious during movement reversals. In able-bodied individuals, movement reversal at the shoulder and elbow were tightly coupled and reversed synchronously. On the other hand, deafferented

individuals displayed a transient locking of the elbow due to the decoupling (asynchrony) of the movement reversals at the shoulder and elbow. To further confirm the role of proprioception in the control of motion-dependent torques, the same group had subjects complete an elbow flexion task with varying degrees of shoulder excursion to five different targets (Sainburg et al., 1995). Movement to each target location therefore produced varying degrees of motion-dependent torques. In the absence of vision, movement trajectories to all target locations were accurate for able-bodied individuals. In the deafferented individuals, accurate movements were only observed for movements to the target locations that produced the least amount of motion-dependent torques. However, as the subject moved to targets where the requirement to control interaction torques became larger, so did errors in the movement.

Combining data from inverse dynamics and electromyography (EMG) can provide further insights into the association between limb kinetics and the motor command (Zernicke and Smith, 1996; Zajac et al., 2003). Impairments in muscle activation patterns in the absence of proprioception can even be seen during single-joint movements. For example, during a simple elbow flexion task to a target, there is an initial centrally driven agonist burst (biceps) to initiate movement, followed by a subsequent antagonist (triceps) burst timed with peak velocity to decelerate the limb, and a final agonist burst, timed with peak deceleration to arrest the limb at the target position (Forget and Lamarre, 1987). Deafferented subjects are able to plan, initiate and move to the target, however the antagonist burst and the second agonist burst are not tightly coupled with peak velocity and peak deceleration, which leads to undershooting and overshooting the target (Forget and Lamarre, 1987). Furthermore, during multi-joint movements,

inverse dynamics along with EMG data in able-bodied subjects show that muscle activity is precisely timed to compensate for interaction torques (Sainburg et al., 1995). On the other hand, deafferented individuals fail to coordinate their muscle activity with respect to the interaction torques; instead, they co-contract the flexors and extensors in a possible attempt to minimize these interactions (Sainburg et al., 1995).

The ability to control inter-segmental dynamics is also important for normal and adaptive gait. The cerebellum receives proprioceptive information (Bosco and Poppele, 1997; 2001) and is an important structure in controlling multi-joint movements and inter-segmental dynamics (Bastian et al., 1996). Recently, it has been shown that cerebellar ataxia (uncoordinated walking) is due to deficits in intra-limb coordination (Ilg et al., 2007; 2008). Individuals with cerebellar ataxia are unable to control resulting interaction torques leading to excessive limb flexion during gait (Ilg et al., 2007; 2008). A similar pattern is upheld in these individuals during obstacle crossing. When stepping over obstacles, they exhibit excessive toe-elevation (Morton et al., 2004). Joint dynamics analysis reveals that the active knee flexor torque does not modulate its activity to the motion-dependent torques, which leads to hypermetria (Morton et al., 2004).

Again, deafferented subjects offer unique insight into the importance of proprioception in controlling the inter-segmental dynamics during gait, but our knowledge of the control of locomotion in these individuals is limited as most of these people have extreme difficulty walking. Nonetheless, a remarkable individual, IW, who has complete proprioceptive loss below the neck has developed multiple compensatory strategies that has allowed him to walk again (Lajoie et al., 1996). IW has reduced the degrees of freedom when walking by locking his knees, increased his base of support,

and adopted a forward stooped posture to constantly visually monitor his steps. The compensatory strategies adopted by this individual are used to minimize the deficits caused by complete proprioceptive loss (Lajoie et al., 1996). IW decreases the degrees of freedom to minimize interaction torques, widens the base of support to maximize balance support and needs to visually monitor his steps, as vision is necessary to compensate for the lost afferent information (Sainburg et al., 1993; Wolpert et al., 1998a).

Deafferented individuals are extreme cases. But the loss of proprioception at even a single joint can also cause alterations in swing limb trajectory and increase the risk of falls. One example of this can be illustrated in people with diabetes. One of the most common consequences of diabetes mellitus is diabetic sensorimotor neuropathy, which usually affects distal segments (Levin, 1998; Perkins and Bril, 2003). It has been shown that individuals with diabetes mellitus have impaired proprioception at the ankle (Gutierrez et al., 2001; Liu et al., 2010). In these individuals, the risk of tripping and falling during walking is also of concern as they display reduced lead limb toe clearance over an obstacle (Liu et al., 2010). Kinematic gait analysis has revealed larger joint moments in the trail (stance) limb in addition to increased dorsiflexion and greater anterior pelvic tilt during obstacle crossing, resulting in reduced swing-toe clearance in individual with diabetes (Liu et al., 2010). As described earlier, the inability to adequately control stance limb kinetics and kinematics as the swing limb crosses the obstacle can lead to impairments in lead-limb toe clearance (end-point control) (Winter, 1992). Thus, it is possible that the peripheral sensory deficits in people with diabetes could lead to alterations in locomotor control strategies, resulting in impairments in endpoint trajectory during obstacle crossing.

Visual Control of Obstacle Crossing

Patla (1998) eloquently stated that the visual system allows humans to "touch" obstacles at a distance, a characteristic not present in other sensory systems. His use of the word 'touch' was not literal; rather it highlighted the importance of vision in guiding locomotion through a changing environment. Vision is important for scanning the environment from a distance and for identifying the characteristics of potential hazards (e.g. obstacles, different terrains); this is known as visual exteroception (Patla, 1997; 1998; Rhea and Rietdyk, 2007). In addition, vision provides information about self-motion and the movement of body segments relative to the environment and to one another; this is known as visual exproprioception (Gibson, 1958; Patla, 1997; 1998; Rhea and Rietdyk, 2007).

Visual exteroceptive information is sampled intermittently during locomotion and used to plan and initiate movements (feedforward control). In a unique study, participants walked in a number of different environments while choosing when they wanted access to visual information via opaque glasses that became translucent at a push of a button (Patla et al., 1996). The number of visual samples taken was correlated to the difficulty and precision required of the task (Patla et al., 1996). During normal overground walking, participants only took visual samples for 10% of the entire movement. As the requirements of the task became more difficult (e.g. obstacles, holes, precise foot placement) the number of visual samples increased, to up to 40% when holes in the ground were present. In most cases, it was the number of visual samples taken that increased rather than the duration of individual samples (Patla et al., 1996).

Similar gaze behavior patterns have been shown during obstacle crossing, where participants spend the majority of their time in "travel fixation" while intermittently fixating on the obstacle and the surrounding area (Patla and Vickers, 1997). As a person moves toward an obstacle, the eyes are not focused on a precise location; rather they are fixated on the ground ahead and move along with the body (travel fixation) (Patla and Vickers, 1997; 2003). The optic flow generated is used to provide information about self-motion and the environment to control the velocity of locomotion (Gibson, 1958; Patla and Vickers, 1997; Warren, 1998; Patla and Vickers, 2003). In addition to travel fixation, during the approach phase the eyes intermittently scan the obstacle and the surrounding area 2-3 steps prior to the obstacle. During the obstacle crossing step, humans do not fixate on the obstacle, rather they sample the landing area to ensure safe foot placement (Patla and Vickers, 1997).

Intermittent sampling of the environment and the characteristic of looking to an area prior to arrival attests to the feedforward control based on visual exteroceptive information. Feedforward control allows visual exteroceptive information to be captured and stored for an upcoming movement (Patla, 1998; Graci et al., 2010; Marigold and Drew, 2011). This hypothesis was tested in a simple task where participants walked along a walkway and crossed over an obstacle while visual information was manipulated (Mohagheghi et al., 2004). Each trial contained a dynamic visual sampling phase (first 2 to 3 steps) followed by an approach phase (next 3 steps) followed by stepping over the obstacle. Vision was always provided during the dynamic visual sampling phase, but was occluded for the rest of the trial for half of the participants. The results showed that providing vision in just the initial dynamic visual sampling phase was sufficient to extract

the spatial location, and height characteristics of the obstacle to complete the task (Patla, 1998; Mohagheghi et al., 2004). However, lead toe clearance was elevated, and lead and trail limb horizontal distance from the obstacle increased when vision was not available in the approach phase (Mohagheghi et al., 2004; Patla and Greig, 2006). In the absence of vision the exact position of our limbs in relation to the environment is not known, thus safety strategies must be implemented to decrease the chances of contacting the potential hazard. Although visual exteroceptive information can be used in a feedforward manner to plan and initiate the appropriate motor commands, optimal toe clearance height, ideal foot placement and most importantly minimizing the incidence of tripping and falling appears to rely on online visual exproprioceptive information (Patla and Greig, 2006; Graci et al., 2009; 2010).

Intriguingly, the control of limb placement prior to toe-off poses a greater risk for unsuccessful obstacle crossing than actual lead limb toe clearance (Patla and Greig, 2006; Lajoie and Drew, 2007). The feedforward control of exteroceptive information is enough to extract the obstacle height and complete the task within a safety margin. However, maintaining proper foot placement in relation to the spatial location of the obstacle requires visual exproprioception (Patla and Greig, 2006; Lajoie and Drew, 2007). This becomes evident in a task where humans are required to cross obstacles with and without vision, while the initial visual information is manipulated. The absence of vision during the approach phase (regardless of the visual information prior to this) leads to a significant number of unsuccessful steps over the obstacle (average of 53% of all steps resulted in obstacle hits). Analysis of lead and trail limb placement before obstacle crossing reveals that unsuccessful trials were due to inappropriate placement of the lead

limb prior to toe off (Patla and Greig, 2006). In the full vision trials, low variability was observed in lead-limb placement before toe-off, whereas in the obstructed vision trials, large variability was seen between trials. Highly variable and inaccurate lead-limb placement led to unsuccessful obstacle crossing (Patla and Greig, 2006). This group concluded that on-line visual information is necessary for successful obstacle crossing (Patla and Greig, 2006). In other words, visual exproprioception of the lower limbs is needed for accurate foot placement.

Spatial cues relevant to obstacle position can drive proper lead and trail foot placement relative to the obstacle when vision is obstructed (Rietdyk and Rhea, 2006; Graci et al., 2010). This is exemplified when humans are asked to cross an obstacle with and without vision, and in the presence or absence of a doorframe placed around the obstacle (providing information about its spatial location) (Rietdyk and Rhea, 2006; Graci et al., 2010). Lead and trail-limb horizontal distance from the obstacle before toe off, and lead toe clearance height over the obstacle increased when both vision and the position cue were unavailable. In contrast, when the position cue is available, lead and trail horizontal distance returned to full vision values, even though visual input about the obstacle was blocked. This suggests that the visual exproprioceptive system is able to extract the relative position of the obstacle in relation to the eyes/head (upper visual field was unobstructed) (Rietdyk and Rhea, 2006; Graci et al., 2010). Proprioceptive information from the lower limbs can then be integrated with this information to understand the position of the lower limbs relative to the head/eyes; this relationship could then theoretically drive proper foot placement (Rietdyk and Rhea, 2006). These finding support and extend the results of Patla and Greig (2006); it is not visual

exproprioception of the lower limbs that is needed, it is on-line visual exproprioception of the body in relation to the obstacle that is needed to drive proper foot placement. However, on-line visual exproprioception of the lower limbs is needed to precisely control toe-trajectory height over the obstacle (Rhea and Rietdyk, 2007)

Impairments in gaze behavior may be attributed in part to low levels of mobility self-efficacy and a fear of falling. Self-efficacy on mobility tasks of daily living contribute to the fear of falling and ultimately greater functional decline (Tinetti et al., 1990; Li et al., 2002; Tinetti and Powell, 2008). Individuals who perceive themselves at risk or unable to do mobility tasks of daily living exhibit a greater fear of falling and are at a greater risk of experiencing a fall (Tinetti et al., 1990; Friedman et al., 2002; Lajoie and Gallagher, 2004; Li et al., 2005). It has recently been shown that individuals who have previously experienced a fall ('high-risk fallers') display altered gaze behavior during a skilled walking task (Yamada et al., 2011; 2012). Although self-efficacy and fear of falling was not quantified in the sample of high-risk fallers studied by Yamada and colleagues, previous studies, including a large prospective, observational study of >2000 participants (Friedman et al 2002), showed that falls history, fear of falling, and balance self-efficacy are strongly associated (Tinetti et al., 1990; Friedman et al., 2002; Lajoie and Gallagher, 2004; Li et al., 2005). The deficits in gaze behavior for high risk fallers was displayed in a task where participants traversed through an environment while specifically stepping on required targets while avoiding others (Yamada et al., 2011; 2012). Participants categorized as low risk fallers generally fixated on targets two to three steps ahead, whereas high-risk fallers fixated on the upcoming foot target (Yamada et al., 2012). In fact, errors in stepping increased when a visual sample was taken closer to the

target. This increased reliance on vision limits the amount of feed-forward (adaptive) control during skilled walking tasks.

Summary and Rationale

The ability to cross obstacles is dependent on the integration of visual and proprioceptive information (Marigold et al., 2011). Vision is essential in identifying and extracting the characteristics of potential hazards (i.e. obstacles), while proprioception is important for controlling inter-segmental dynamics, in addition to maintaining an internal representation of the environment and limbs (Sainburg et al., 1993; Patla, 1998; Marigold and Drew, 2011). The ability to integrate information about the obstacle with limb position is crucial for adequate lower limb control, whilst minimizing the chance of falling during obstacle crossing. Deficits in sensorimotor control could also contribute to lower balance and ambulation self-efficacy, which in turn could limit performance of skilled walking tasks, including obstacle crossing in people with m-iSCI. Given the important role of proprioception in the feed-forward control of movement, along with the importance of obstacle crossing as an indicator of functional ambulation, our overall objective here was to evaluate obstacle crossing performance in ambulatory individuals with m-iSCI. Specifically, we aimed to determine the changes in gaze behavior and lower limb kinematics that occur during obstacle crossing following an m-iSCI while considering proprioceptive sense and balance and ambulation self-efficacy.

Hypothesis 1: m-iSCI subjects will look at the obstacle more frequently (# of glances) and for a longer period of time (gaze duration) during full vision obstacle-crossing trials.

Moreover, gaze behavior will be associated with proprioceptive sense and balance and ambulation self-efficacy in people with m-iSCI.

Hypothesis 2: m-iSCI subjects will show significant differences compared to controls in obstacle-crossing strategies when vision is occluded.

Hypothesis 3: The exacerbation of obstacle crossing difficulties when vision is restricted will be associated with the degree of proprioceptive deficits in people with m-iSCI.

Methods

Study Design: Cross-sectional.

Subjects: 9 individuals with motor-incomplete SCI and 10 age (+/- 5 years) and sex matched able-bodied (AB) controls were recruited. The inclusion criteria for the SCI subjects were: 1) SCI at least 9 months ago; 2) motor- incomplete spinal cord injury (as assessed by the American Spinal Injury Association Impairment Scale (AIS) C or D) at or above T10; 3) able to walk at least 5 m with or without an aid; and 4) normal or corrected to normal (with contact lenses or glasses) visual acuity of 20/40 (confirmed by the Snellen chart examination). The exclusion criteria for the SCI subjects were: 1) AIS A or B classification (complete paralysis); 2) presence of any musculoskeletal injury or other cardiovascular or neurological condition affecting mobility or sensory function; 3) severe spasticity interfering with walking function; and 4) weight >136kg or height >1.85 m (limits of the Lokomat).

Protocol

Session 1: Baseline Functional Assessments

Proprioceptive Acuity (SCI and AB)

Proprioceptive sense (static position sense and movement detection threshold) at the hip and knee of both lower limbs was measured using custom-written software of the Lokomat (Hocoma AG, Volketswil, Switzerland) (Domingo and Lam, 2014; Domingo et al., 2013). General Procedure: Participants were suspended in the air with an overhead harness system and their legs strapped to the Lokomat. A large drape covered the subjects' legs to block visual input about limb position, thus forcing the participants to rely on their proprioceptive sense for this task. A joystick was positioned in front of the participants. Static Position sense: Joint matching accuracy was tested at both hip and knee joints. The test joint was moved to a target angle (25° flexion or 25° extension), and the subject was asked to memorize this position. The Lokomat subsequently moved the joint away from the memorized position (distractor position). Subjects were then asked to use the joystick (which controlled the Lokomat's legs) to position their test joint back to the memorized position. The use of the joystick eliminated the potential confounding variations between subjects in their ability to voluntarily control the lower limb. Movement Detection Sense: Movement detection threshold was also tested at both hip and knee joints. The Lokomat moved the test joint either into flexion or extension at 3 different speeds (0.5, 1 and 2 deg/sec). Subjects were instructed to press a button on the joystick as soon as they detected a change in joint position. They were also asked to state whether the joint had moved into flexion or extension.

Clinical Measures (SCI only)

A series of standard functional assessments were used to characterize the motor and sensory impairments of the participants with m-iSCI.

Lower extremity strength was measured by using the Lower Extremity Motor Score (LEMS) of the AIS. The LEMS represents a combined score from manual muscle testing of the hip flexor, knee extensor, ankle plantarflexor, ankle dorsiflexor and great toe extensor muscles. Muscles were tested in accordance with AIS standards by a physical therapist (Maynard et al., 1997; Waring et al., 2010). Muscle strength was scored on a scale from 0 to 5 (0 = total paralysis, 1 = palpable or visible contraction, 2 = active movement; without gravity, 3 = activate movement against gravity, 4 = active movement against partial resistance, 5 = active movement against full resistance, or NT = not testable).

Ambulatory capacity was measured using the self-selected and maximum 10meter walk test (10MWT) (Jackson et al., 2008) and the Spinal Cord Injury-Functional Ambulation Profile (SCI-FAP) (Musselman et al., 2011). For the 10MWT, subjects walked along a 12-m walkway at their most comfortable speed and at their fastest speed. Walking speed was calculated using the time required to traverse the middle 10 m, as measured by a stopwatch. The SCI-FAP is a timed test of 7 walking tasks reflecting walking skills necessary for everyday mobility (e.g. obstacle crossing, stairs) (Musselman et al., 2011; Musselman and Yang, 2013). The time required to complete each subtask was recorded and multiplied by a factor corresponding to the assistive device or level of

manual assistance needed. The 7 sub-scores are summed to provide a total score. Lower scores indicate better function.

Balance was assessed using the Berg Balance Scale (BBS) (Stevenson, 2001; Blum and Korner-Bitensky, 2008; Wirz et al., 2010). The BBS is a 14-item scale, using a variety of tests to measure static and dynamic balance function. Each item is given a score from 0-4 with 0 indicating poor performance and 4 indicating excellent performance. All items were summed for a maximum score of 56. Higher scores indicate better balance function.

We also used the Ambulatory Self-Confidence Questionnaire (ASCQ) and the Activities-Specific Balance Confidence Questionnaire (ABC) to gauge self-confidence in everyday ambulation and balance tasks (Powell and Myers, 1995; Asano et al., 2007). The ASCQ is a 22-item questionnaire that asks participants to rate their self-confidence on a scale of 0 (not at all confident) to 10 (extremely confident) on a variety of mobilityrelated tasks (e.g. "*how confident are that you are able to walk on slippery ground: for example icy or wet surfaces*?"). The ABC Questionnaire has 16-items and also asks participants to rate their self-confidence on a scale of 0 (not at all confident) to 100 (extremely confident) that they will not lose their balance when completing a task (e.g. "*how confident are you that you will not lose your balance or become unsteady when you walk outside on icy sidewalks*?")

Determining Obstacle Height (SCI and AB)

Acknowledging the heterogeneous profile of the SCI population, we attempted as much as possible to control for differences in motor capacity by scaling the obstacle height to each person's motor abilities. Average toe height and maximum toe height during treadmill walking (larger number of steps) were extracted. Obstacle height was then set for each participant as follows: maximum toe height minus average toe height, divided by 4 plus the average step height ($(\frac{Max-Avg}{4}) + avg$) (Fig. 2).

Session 2: Obstacle Crossing Experiment

Infrared-emitting diodes (Optotrak, NDI, Waterloo, Canada) were placed bilaterally over the hallux on the tip of the subject's shoe, the 1st metatarsal, 3rd metatarsal and 5th metatarsal. Infrared emitting diodes were also placed on the obstacle indicating its height. This allowed us to obtain toe position relative to the obstacle. Marker data was collected at a sampling frequency of 100Hz.

Electrogoniometers were placed bilaterally across the ankle, knee and hip joints to obtain lower limb joint kinematic data. These signals were collected at a sampling frequency of 1000Hz.

Gaze behavior was recorded using the Dikablis infrared eye tracker (Dikablis, Ergoneers GmBH, Germany). The video-based monocular eye tracker is head mounted and data were recorded at a sampling frequency of 25Hz. The Dikablis eye tracker records videos of both the environment (field camera) and the pupil (eye camera). A
common synchronization pulse was sent to all systems for off-line synchronization of the data.

Experimental Procedures

Subjects were positioned between parallel bars and 2.5 stride lengths (based on the trail limb) away from an obstacle positioned between a doorframe (indicating the spatial location of the obstacle). Subjects were instructed to take their first step with their weaker (non-dominant) leg. This leg was defined as the trail limb (the second limb to cross the obstacle). Two conditions were presented (no goggles and goggles) and 8-10 trials were collected in each condition. Subjects were permitted to use the parallel bars and their usual orthosis if required.

Figure 2 shows a diagram of the experimental setup. The parallel bars form the length of the walkway (3 meters in length). The width of the parallel bars was adjusted to each subject's preference. We used parallel bars to minimize the potential confounding effects of the use of different gait aids. The doorframe, which was 216 cm in height and 100 cm wide, was constructed from black ABS tubing (15.5 cm diameter) and positioned around the obstacle. The base of the obstacle was made of two plywood squares (61cm X 61cm) that were inserted directly into the laboratory floor. Two height adjustable vertical aluminum tubes were inserted onto the front edge of the platform. The obstacle then rested on the 2 aluminum tubes on either side. The obstacle itself was 47.5cm wide with a depth of 1cm, and made of a wooden dowel (3.3 cm diameter) that was covered in black cloth and draped to the ground. The height of the obstacle was adjustable by changing the

position of the aluminum supports. This design made the obstacle very light and safe; any contact with the obstacle would result in it simply falling off its platform.

All subjects underwent 3 sets of trials:

<u>Baseline condition:</u> Participants were asked to walk along a walkway (2-3 passes) to determine baseline unobstructed walking behavior.

<u>Full vision (FV) condition, no instructions</u>: Subjects walked along the walkway and no specific instructions were provided, other than to "step over the obstacle" and walk at their self-selected speed.

Obstructed vision (OV) condition, instructed to look straight: Participants donned dribble goggles to occlude the lower visual field and were asked to maintain a straight-ahead gaze while stepping over the obstacle. The dribble goggles prevented the participants from relying on peripheral visual feedback (Rietdyk and Rhea, 2006; Graci et al., 2010). In this condition, it was assumed that participants relied more on lower limb proprioceptive feedback to complete the task (Sainburg et al., 1995). The dribble goggles do not restrict vision of the doorframe, allowing it to act as an exteroceptive cue about the spatial location of the obstacle along the walkway (Rietdyk and Rhea, 2006; Graci et al., 2010)

Data Analysis

Custom-written routines in MATLAB (MathWorks, Inc. Natick, MA) were used for all off-line data analysis. All kinematic data were low-pass filtered with a 4th-order dual-pass Butterworth filter at 6 Hz. Data were divided into individual strides by defining

heel contact and toe off times based on the horizontal (anterior-posterior) excursions of the toe marker.

Four measures related to the position of the toe relative to the obstacle were extracted to define the following obstacle crossing parameters:

- Lead horizontal distance (HORZ-L), defined as the horizontal distance between the toe marker on the lead limb and the front edge of the obstacle during the stance phase of the step over the obstacle, normalized to stride length.
- 2) Trail horizontal distance (HORZ-T), defined as the horizontal distance between the toe marker on the trail limb and the front edge of the obstacle during the stance phase of the step over the obstacle, normalized to stride length.
- 3) Lead toe clearance (VERT-L), defined as the vertical distance between the marker on the tip of the lead foot and the top edge of the obstacle at the point of crossing, normalized to obstacle height.
- 4) **Trail toe clearance (VERT-T),** defined as the vertical distance between the marker placed on the tip of the shoe of the trail limb and the top edge of the obstacle at the point of crossing, normalized to obstacle height.

Because the trail limb toe marker went out of view of the cameras, trail horizontal distance analysis could not be completed for SCI03 and trail toe clearance analysis could not be completed for AB06, 07 and 10. Trail toe clearance analysis could also not be

completed from SCI 03, 06, 08 and 09 because they could not cross the obstacle with their trail limb (see Results).

Joint kinematic data were quantified by calculating the peak hip, knee, and ankle joint (dorsi)flexion angles during the swing phase of each step. Due to equipment error, AB08 was excluded from lead limb joint kinematic analysis, AB09 and 10 excluded from trail limb joint kinematic analysis, AB07 excluded from trail peak hip and ankle (dorsi)flexion analysis, and AB05 from trail peal ankle (dorsi)flexion analysis. As mentioned above, 4 SCI participants had to be excluded from trail limb joint kinematic analysis because they could not cross the obstacle with their trail limb (see Results)

Changes in obstacle crossing parameters and joint kinematics were defined as the difference in HORZ-L/HORZ-T/VERT-L/VERT-T or peak hip/knee/ankle angles between OV and FV conditions. We also calculated the trial-to-trial coefficient of variation (CoV) of each parameter in each subject, defined as standard deviation divided by mean for the kinematic parameter being evaluated.

Gaze data were processed with Dikablis Analysis 2.5 and D-Lab 2.5 software (Dikablis, Ergoneers GmBH, Germany) and custom-written MATLAB code. Two parameters were extracted to define *gaze behaviour* with respect to the steps prior to obstacle crossing: 1) **number of saccades**, defined as the number of eye displacements towards the obstacle; and 2) **gaze fixations**, defined as the duration of each saccade to the obstacle. AB10 was excluded from this analysis due to equipment error.

Proprioceptive sense was defined by static position sense and movement detection threshold scores. For static position sense, we calculated the absolute average difference

between the actual and target position across 6 trials; smaller differences correspond to better static position sense. A movement detection score for each joint was calculated by the sum of 1) joint excursion before the button was pressed normalized to maximum absolute joint excursion (10 degrees); and 2) the verbal response to the direction of movement. The maximum normalized joint excursion score for each trial was 1, and a score of 0 was given if the verbal response was correct and 1 if the response was incorrect. Thus, the maximum possible score (worst performance) for a given trial was 2. Movement detection threshold at three different speeds (0.5, 1.0, 2.0 deg/s) was calculated, giving a total possible maximum score of 6. Higher scores indicate worse movement detection threshold.

Statistical Analysis

SPSS v.20 statistics (IBM Corp, Armonk, NY) was used to conduct all statistical analysis. The critical value for significance of all statistical tests was set at a αvalue of 0.05. Trends were defined by p<0.10. Descriptive statistics were used to describe baseline demographic characteristics of the subject groups. Independent samples t-tests were used to confirm that the SCI and AB were comparable for age, height, and weight. Independent samples t-tests were also used to compare proprioceptive sense and gaze behavior in the FV condition between the SCI and AB subjects. Descriptive statistics were used to summarize the number of obstacle hits observed during the experiment.

The following assumptions were tested: homogeneity of variance using Mauchly's Test of Sphericity and Levene's Test of Error Variances. Normality was tested using the Shapiro-Wilk test. If the homogeneity tests were violated the Greenhouse-Geisser adjustment was used.

A 2 (SCI, Controls) X 2 (FV, OV) analysis of variance (ANOVA) was used to compare all toe kinematic parameters between groups and conditions.

A 2(SCI, Controls) X 3 (unobstructed, FV, OV) ANOVA was used to describe changes in peak ankle, knee and hip flexion angles of the lead and trail limbs among the different conditions and between the groups. When applicable, a Bonferroni adjustment was used for post hoc pairwise comparisons.

When statistically significant comparisons were found in the ANOVAs, partial Eta squared (η^2) was reported to identify the effect size. An effect size of 0.2 is considered small, 0.5 medium and 0.8 large (Cohen, 1990). Power was also reported to understand the reliability of our results.

Raw data comparing proprioceptive sense and the change in obstacle crossing parameters between OV and FV conditions were plotted using scatterplots to describe their relationships with proprioceptive sense. Pearson's correlation coefficients (r) and their 95% confidence intervals were calculated to estimate the relationship between these variables.

Results

Subject Characteristics

Nine subjects with chronic SCI (> 1 year post-injury) and 10 age-and sex-matched controls participated in this study. Table 1 presents the baseline subject characteristics and Table 2 presents the values of the functional assessments conducted on persons with SCI. There were no significant differences between the SCI and AB group in terms of age (t(17) = -0.439, p = 0.666), height (t(17) = -0.728, p = 0.477), and weight (t(17) = 0.566, p = 0.578). None of the AB and 6 of the SCI subjects used the parallel bars during the experiment. All of the SCI who required a hand-held gait aid during walking used the parallel bars during the experiment (Table 2), and of these SCI08 and 09 also required a Dictus brace or ankle-foot orthosis to support foot clearance on their trail limb.

Our tests of proprioceptive sense revealed that the subjects with SCI had significant impairments in static position and movement detection sense. Overall proprioceptive sense was determined by summing the static position sense and movement detection scores from the lead and trail limb together. The SCI group presented with significantly worse overall static position sense (t(16) = -3.487, p = 0.003) and movement detection (t(17) = -3.146, p = 0.006) compared to the AB group (Fig. 3).

Scaling Obstacle Height

We were successfully able to scale for obstacle height, as the SCI participants did not saturate towards their maximum step height when stepping over the obstacle with their lead limb in either condition (Fig. 4). Moreover, we observed no relationship between LEMS and toe clearance height (lead and trail) for both conditions (Fig. 5)

Gaze Behavior

Figure 6A illustrates the average number of saccades over the two strides prior to and the stride over the obstacle. There was a pattern for the SCI subjects to continue to gaze at the obstacle as they approached it, although there were no statistically significant differences between the groups (two strides before: t(16) = -0.310, p = 0.761; one stride before: t(16) = -1.013, p = 0.326; step over: t(16) = -1.466, p = 0.179). Although the SCI subjects tended to look at the obstacle more often than the AB group, there was no significant difference in the total number of saccades between groups (SCI: t(16) = -1.7, p = 0.107, Fig. 6B). Moreover gaze fixations in the SCI participants tended to be smaller in duration, although this was not significantly different between groups (Fig. 6C; t(16) = 1.298, p = 0.223)

The total number of saccades and mean gaze duration, alongside the number of saccades over the 2 strides prior to crossing the obstacle, were plotted against overall static position sense and movements detection threshold to examine if there was a relationship between gaze behavior and overall proprioceptive sense (Fig. 7 and 8). There appeared to be a positive relationship between overall proprioceptive sense with mean gaze duration (Fig. 7B) and the number of saccades towards the obstacle in the stride prior to crossing the obstacle (Fig 8B). In addition, there also appeared to be a negative relationship with the number of saccades towards the obstacle in the 2 strides prior to crossing and overall proprioceptive sense. (Fig. 8A)

The total number of saccades and mean gaze duration was also plotted against normalized scores on the ABC and the ASCQ (normalized to maximum total score) to examine the relationship between gaze behavior and balance/ambulation self-efficacy (Fig 9). There was a negative relationship between the ABC and ASCQ and the total number of saccades and mean gaze duration.

Obstacle Crossing Behaviour

Figure 10 depicts the number of obstacle hits by the lead and trail limbs in both condition for each participant. In general, the SCI participants hit the obstacle more often than the AB participants for both the lead and trail limbs in both conditions. The number of obstacle contacts was greater in the OV condition and in the trail limb. In the lead limb, there were a total of 6 obstacle hits (SCI = 5, AB = 1) in the FV condition and 20 (SCI = 16, AB = 4) in the OV condition. In the trail limb, there were a total of 43 obstacle hits (SCI = 40, AB = 3) in the FV condition and 56 (SCI = 45, AB = 16) in the OV condition. SCI03, 06 08 and 09 could not cross the obstacle with their trail limb and thus hit the obstacle in every trial. These participants accounted for 40 contacts by the SCI group in both the FV and OV conditions. Moreover, because these participants were unable to cross with their trail limb, their trail limb toe clearance height, and joint kinematic data were not included in the analysis.

Obstacle Crossing Parameters

Overall trajectories of lead and trail limb kinematics of a representative AB and SCI participant are plotted in Figures 11 and 12, respectively. As expected, flexion of the lower limbs and vertical toe trajectory height was greater during obstacle crossing. The AB subject showed little difference in gait patterns between full vision (FV) and obstructed vision (OV) conditions while the SCI subject tended to show higher stepping pattern in the OV condition. There was little modulation of trail limb kinematics between unobstructed and obstacle-crossing trials, likely because the weaker limb was designated to be the trail limb in the SCI group.

Toe Kinematics

Normalized lead toe clearance (VERT-L) and trail toe clearance (VERT-T) over the obstacle during the FV condition was comparable between the AB and SCI groups (Fig. 13A), again indicating that we were successful in normalizing obstacle height to lead limb motor capacity. Although lead toe clearance (VERT-L) and trail toe clearance (VERT-T) tended to be greater in the OV condition compared to FV in both groups, there were no significant main effects of condition for any of these parameters (VERT-L: F(1,17) = 2.922, p = 0.106; VERT-T: F(1,10) = 0.082, p = 0.781).

Normalized lead horizontal (HORZ-L) and trail horizontal (HORZ-T) distance during the FV condition was also comparable between the AB and SCI groups (Fig. 13B). Trail horizontal distance significantly increased (main effect of condition) during the OV condition (F(1,16) = 9.150, p < 0.001, partial η^2 = 0.364, observed power = 0.810. On the other hand, no effect of condition was seen for lead horizontal distance (F(1,17) = 2.357, p = 0.143).

There were also no significant main effects of group for any of the lead or trail limb obstacle crossing parameters (HORZ-L: F(1,17) = 2.124, p = 0.163; VERT-L: F(1,17) = 1.066, p = 0.316; HORZ-T: F(1,16) = 0.142, p = 0.711; VERT-T: F(1,10) = 1.928 p = 0.195) although SCI subjects were seen to have reduced lead horizontal distance compared to AB subjects (Fig. 13B).

To further examine if there was any relationship between proprioceptive sense and obstacle crossing performance, we first calculated the change in toe kinematic parameters between FV and OV conditions, then plotted those against lead and trail limb proprioceptive sense scores (static position sense and movement detection threshold). There appeared to be a positive relationship between toe clearance and proprioceptive sense (Fig. 14, 15 and 16), especially for VERT-T and lead proprioceptive sense (Fig. 14A). There also may be a positive relationship between HORZ-T and trail limb proprioceptive sense (Fig. 15B).

Variability in Toe Kinematics

Average variability (coeffiient of variation, CoV) of toe clearance and horizontal distance for both limbs is plotted in figure 17. VERT-L and HORZ-L were significantly more variable in the OV compared to the FV condition, while HORZ-T trended towards significance (HORZ-L CoV: (F(1,17) = 9.625, p = 0.006, partial η^2 = 0.362, Observed Power = 0.832; VERT-L CoV: (F(1,17) = 7.174, p = 0.016, partial η^2 = 0.297, Observed Power = 0.714; HORZ-T CoV: F(1,17) = 3.386, p = 0.083, partial η^2 = 0.166, Observed Power = 0.412). No effect of condition was observed for trail toe clearance variability (VERT-T CoV: (F(1,10) = 0.789, p = 0.395). No interaction effects were observed.

SCI subjects presented with significantly greater variability than the AB subjects in trail horizontal distance (F(1,17) = 5.858, p = 0.027, partial η^2 = 0.256, Observed Power = 0.626). No other group effects were observed.

To examine if there was any relationship between proprioceptive sense and variability in toe kinematic parameters, we plotted the change in toe kinematic variability against proprioceptive sense scores (static position sense and movement detection threshold). The only apparent pattern that emerged was a positive relationship between the variability in VERT-T and lead limb proprioceptive sense (Fig. 18A). There also seemed to be a slight positive relationship between the variability in HORZ-T and with lead limb proprioceptive sense (Fig. 18B). Minimal to no relationships were observed between proprioceptive sense and all other toe kinematic variability measures (Fig. 19 and 20)

Joint Kinematics:

Average and individual subject's peak hip, knee, and ankle (dorsi)flexion angles are plotted for the lead and trail limbs in figure 21 and 22.

SCI subjects had significantly lower peak knee flexion angles in the lead limb compared to the AB group across all conditions (F(1,16) = 4.473, p = 0.05, partial η^2 = 0.218, observed power = 0.511), but there were no significant main effects of group for peak trail limb knee angle or the hip or ankle angles in either the lead or trail limb.

There was a main effect of condition on all lead and trail limb joint angles (lead ankle: $(F(2,32) = 18.083, p < 0.001, partial \eta^2 = 0.531, observed power = 1.000; lead knee: F(1.336,21.379) = 82.536, p < 0.001, partial \eta^2 = 0.838, observed power = 1.000; lead hip: F(1.301,22.121) = 144.227, p < 0.001 partial \eta^2 = 0.895, observed power = 1.000, trail ankle: F(2,16) = 3.936, p = 0.041 partial \eta^2 = 0.330, observed power = 0.621: trail knee: F (1.348,14.831) = 116.348, p < 0.001 partial \eta^2 = 0.914, observed power =$

1.000; trail hip: F(2,20) = 63.589, p <0.001, partial $\eta^2 = 0.864$, observed power = 1.000), but there were no significant interaction effects. Post hoc analysis revealed a significant difference for all joint angles between unobstructed walking and obstructed walking with FV (p < 0.001 for all joints) and OV (p < 0.001 for all joints), except for the trail ankle, which was trending towards significance between unobstructed walking and obstructed walking with OV (p = 0.056). There was also a significant difference between FV and OV conditions for lead peak hip angle (p < 0.001), trail peak knee angle (p = 0.033), and trail peak hip angle (p = 0.014), but only a trend for trail peak ankle angle (p = 0.056) and no difference for the lead knee or ankle.

The change in peak hip, knee, and ankle flexion angles between FV and OV conditions for both the lead and trail limbs are plotted in figure 23. The increase in peak hip flexion from FV to OV conditions was comparable between the AB and SCI groups (lead hip difference: t(17) = 0.338, p = 0.739; trail hip difference; t(10) = 0.020, p = 0.984). At the knee, SCI subjects demonstrated a significantly greater increase in lead peak knee flexion angle compared to the AB group (t(16) = -2.298, p = 0.035). There were no other significant differences in the change in joint kinematic variables from FV to OV conditions between the groups.

Discussion

In this project, we sought to evaluate the potential impact of sensory deficits, in particular proprioceptive sense, on obstacle crossing performance, joint kinematics and gaze behavior, while considering balance and ambulation self-efficacy in ambulatory individuals with a m-iSCI. These participants displayed the ability to modulate their joint kinematics when crossing an obstacle but seemed to have greater reliance on vision to complete the task. It is possible that impairments in proprioception combined with balance and ambulation self-efficacy could have contributed to the alterations seen in gaze behavior as well as the gait kinematic strategies during obstacle-crossing.

Persons with m-iSCI have impaired static position sense and movement detection sense

A SCI can result in various combinations of motor and sensory impairments. There is currently no 'gold standard' for identifying impairments in proprioceptive sense (static position sense and movement detection threshold). Recently, our lab has developed a valid and reliable tool to measure lower limb static position sense and movement detection threshold (Domingo and Lam, 2014; Domingo et al., 2013). This tool has given us the unique opportunity to accurately and non-invasively quantify proprioceptive sense in humans. While the impacts of motor deficits in SCI and its impact on the recovery of walking have been extensively explored (Wessels et al., 2010; Morawietz and Moffat, 2013) very little is known about the impact of sensory deficits, particularly proprioceptive sense, and its role in the recovery of walking following SCI. This new tool allows us to integrate measures of proprioceptive sense alongside existing measures of motor impairment to comprehensively evaluate the recovery of skilled walking function. Indeed, the results of this study showed that SCI participants have impairments in both static position sense and movement detection threshold. It is notable that based on the clinical assessments of function we used here, the majority of the participants with SCI in our study would be considered 'high functioning', with more than half of them with a maximal gait velocity >1.0 m/s and BBS >45 (Schmid et al.,

2007; Blum and Korner-Bitensky, 2008; Bowden et al., 2008; Doğğan et al., 2011) yet with significant impairments in proprioceptive sense (static position sense and movement detection threshold). This not only highlights the specificity of our novel tool, but also stresses the importance of taking into account both motor and sensory impairments in SCI when evaluating movement outcomes and designing rehabilitation strategies for this population.

Do people with m-iSCI have a greater reliance on vision?

Vision is an essential component for identifying potential hazards (i.e. obstacles) in our environment and initiating the appropriate sensorimotor response to complete the task. During obstacle crossing, vision is used in a feed-forward manner and is critical for accurate foot placement and toe clearance (Patla and Greig, 2006). For example, when crossing obstacles AB individuals generally fixate on the obstacle 2 steps prior to crossing it but rarely glance towards the obstacle while stepping over it (Patla and Vickers, 1997). This type of gaze behavior was consistently observed in the AB individuals in our study. They tended to reduce the number of saccades towards the obstacle per saccade. In contrast, the SCI participants showed the opposite response and tended to increase the number of saccades towards the obstacle, with shorter fixations on the obstacle per saccade as they approached it.

Our ability to extract relevant visual information and maintain a spatial representation of the environment in a feed-forward manner to execute a multi-joint goal directed movement is in part due to our proprioceptive system. As evidenced by results

from deafferented individuals, the absence of proprioceptive sense does not result in the inability to move, but rather movements become uncoordinated and clumsy and there is a greater reliance on continuous on-line visual regulation of the limbs to complete a task (Rothwell et al., 1982; Sanes et al., 1984; Sainburg et al., 1993; 1995), Indeed, we observed that m-iSCI individuals with greater proprioceptive deficits seemed to have a greater reliance on vision than the AB group. Previous work in cats and humans have shown that visual occlusion of the obstacle and lower limbs 2 steps prior to crossing an obstacle minimally hinders performance (Patla, 1998; Mohagheghi et al., 2004; Patla and Greig, 2006; Marigold et al., 2011; Marigold and Drew, 2011). These results demonstrate that humans are able to build a spatial representation of their environment and integrate this with an internal representation of their body to accurately complete the movement (Patla and Vickers, 1997; Marigold et al., 2011; Marigold and Drew, 2011). Although we are able to cross obstacles in the absence of vision, visual input allows for more precise control of the limbs by continuously updating the spatial environment and the spatial location of the limbs (Patla and Greig, 2006; Rietdyk and Rhea, 2006). Perhaps, the ability to maintain this internal representation of the environment and the limbs for longer periods of time is altered in persons with m-iSCI. This could explain why participants with a m-iSCI who had greater proprioceptive deficits tended to look at the obstacle more often for longer periods of time.

Self-efficacy may have also played a role in impairments in the feed-forward control of obstacle-crossing strategies. Elderly individuals who are at high risk of falling tend to have lower self-efficacy in activities of daily living (Lajoie and Gallagher, 2004; Tinetti and Powell, 2008; Schepens et al., 2010) and also display altered gaze behavior

that may account for their increased likelihood of experiencing a fall (Chapman and Hollands, 2006; 2007; 2009; Young and Hollands, 2010; Yamada et al., 2012). The majority of our SCI participants had levels of balance and ambulation self-efficacy that would be considered at high risk for a fall when comparing our scores to able-bodied individuals (Lajoie and Gallagher, 2004), those with Parkinson's disease (Mak and Pang, 2009a; 2009b) and those who have suffered a stroke. (Beninato et al., 2009). The gaze behavior patterns observed in our study were similar to those reported by Yamada and colleagues in high risk fallers. We also observed that lower self-efficacy was related to a higher number of saccades and longer gaze durations. This suggests that those with decreased self-efficacy rely heavily on vision until they have crossed the obstacle, consistent with the proposition that high-risk fallers may have impairments in the feedforward control of skilled walking tasks. Given the impairments in proprioception alongside decreased self-confidence it is plausible that m-iSCI participants may have impairments in the feed-forward control of movement and thus rely heavily on vision during obstructed walking.

Is lower limb proprioception critical for foot placement?

During the obstructed visual condition, it seems that both groups tended to increase both lead and trail limb horizontal distance from the obstacle. Previous work has shown that in the absence of direct visual feedback of the limbs, humans adopt a more cautious gait pattern by stepping further away from the obstacle in order to reduce the likelihood of toe-obstacle contact (Patla, 1998; Chou and Draganich, 1998b; Mohagheghi et al., 2004; Patla and Greig, 2006; Rietdyk and Rhea, 2006). It appeared that the SCI

group was able to appropriately modulate lead and trail horizontal distance irrespective of their proprioceptive deficits, as there was no apparent trend in the association between proprioceptive sense and the change in horizontal distance. Previous work has suggested that having vision of the spatial cue (e.g. the doorframe indicating the spatial location of the obstacle) provides information about the position of the head relative to the obstacle. This information is then integrated with lower limb proprioceptive sense to drive accurate foot placement (Rietdyk and Rhea, 2006; Marigold, 2008). The impairments in proprioceptive sense observed in our SCI group did not lead to abnormal foot placement when vision was obstructed. Perhaps visual exproprioception of head position relative to the obstacle, independent of lower limb proprioceptive sense, is enough to drive appropriate foot placement.

Does proprioceptive sense update or maintain the initial motor plan set by vision?

When crossing obstacles under restricted vision conditions, humans generally adopt a safety strategy by increasing lead and trail toe clearance, thus minimizing the chance of contact with the obstacle (Patla, 1998; Rietdyk and Rhea, 2006). However, we did not observe this pattern among our AB group. It is possible that our obstacle, which was created with a safety-first approach for our SCI participants, did not pose a large enough threat to the AB subjects. Our obstacle was designed to pose little danger of tripping in case of contact; it was very light and the consequences of hitting it were minimal. In contrast, the obstacle used by Rietdyk et al (2006) was made of a solid woodbased material (masonite). We even observed that the AB subjects tended to reduce their trail limb clearance height in the OV condition, which is reminiscent of crossing strategies over an imagined obstacle. It has also been shown that trail toe clearance height

is reduced when crossing an obstacle guided from memory compared to a real obstacle (Heijnen et al., 2014). Of course, the memory-guided obstacle poses minimal to no risk. Moreover, trail limb clearance has also been shown to decrease in a linear fashion over multiple trials (Heijnen et al., 2012). Thus the level of risk posed by the obstacle-crossing environment we created could explain the pattern of limb clearance over the obstacle that we observed in our AB group.

The SCI participants on the other hand increased both lead and trail to clearance to a greater extent than the AB group when vision was restricted. It is possible that the greater increase in toe clearance height by the SCI group could be due to a more cautionary strategy compared to the AB group. However, given the impairments associated with a SCI other factors could also have contributed. We observed a positive relationship between lead limb proprioceptive impairments and the change in toe clearance from FV to OV, especially in the trail limb. McVea and colleagues (2007) have shown evidence from cats that during obstacle crossing, the forelimbs provide information to the hindlimbs to guide toe clearance. This group used a paradigm where they stopped the cat for up to 10 minutes once the forelimbs had crossed the obstacle (so the animals were straddling the obstacle), or just prior to the forelimbs crossing the obstacle. At this point the obstacle was lowered without the animals' knowledge. In both these conditions, visual information about the obstacle was the same but in the first condition, the forelimbs experienced crossing the obstacle while in the second condition, obstacle crossing had not yet occurred. They found that when the forelimbs had crossed the obstacle, hindlimb clearance was appropriately modulated even though there was no obstacle present. In contrast, when the forelimbs were stopped prior to crossing and some

time had lapsed, hindlimb trajectory was reduced in comparison to when they straddled the obstacle. Moreover for longer durations hind limb trajectory returned to baseline values. In contrast, when cats straddled the obstacle, the scaling of hindlimb trajectory was maintained for pauses of even up to 10 min. These findings suggest that the active movement of the forelimb over the obstacle provided important information regarding the obstacle to the hindlimbs to guide its trajectory.

In contrast, studies in adult humans suggest that during obstacle crossing, the lead and trail limbs are independently controlled, as lead limb clearance has not been found to scale to trail limb clearance (Mohagheghi et al., 2004; Rietdyk and Rhea, 2006). To better understand this phenomenon, Lajoie et al. (2012) conducted a similar study to McVea and colleagues (2011) in humans. Participants crossed an obstacle with one limb, and were then asked to pause and straddle the obstacle between the legs for up to 2 minutes before stepping over the obstacle with the other leg. Three different experimental conditions were tested to independently understand the contributions of vision, lead limb proprioception and the efference copy in maintaining a neural representation of the obstacle to drive accurate trail limb trajectory. Their results showed that when vision of the obstacle was available during lead limb crossing, trail limb clearance was also appropriately modulated. However, when the lead limb was passively moved over the obstacle (thus eliminating the efference copy), or when weights were added to the lead limb (thus altering proprioceptive sense), trail limb toe clearance height was not proportionally scaled. Based on these results, this group suggested that visual information regarding the obstacle, but not lead limb proprioceptive sense or efference copy, is important in guiding trail limb trajectory. However, these conclusions may have been

premature as this group did not dissociate between the initial spatial properties of the obstacle defined by the visual system and those acquired by the experience of the lead limb over the obstacle. Because vision is used in a feedforward manner it is likely that proprioceptive sense was used to maintain and update the motor plan (Andujar and Drew, 2007; Andujar et al., 2010; Lajoie et al., 2010; Marigold et al., 2011). Vision is initially used to create the appropriate motor plan, but proprioceptive sense from the lead limb may be important in maintaining or updating the spatial properties of the obstacle based on the success of its trajectory (McVea & Pearson 2007). If this is true, then altering the weight of the lead limb without any consequences to the success of the lead limb trajectory (i.e. obstacle contact) would not have signaled any changes in the spatial properties of the obstacle, thus no change in the motor plan to guide trail limb trajectory. Therefore, the finding that trail limb trajectory was not affected by the addition of weights to the lead limb is not surprising given that the trail limb could have generated its own set of motor commands (Drew et al., 1996) from the original visual input and the lead limb did not provide any new updates about the spatial properties of the obstacle. The role of limb proprioception may be two-fold: 1) to control inter-joint coordination within a limb; and, more globally, 2) to code the end-point trajectory and provide cues about the success of that trajectory in the current task environment in the absence of any other feedback. In this context, Lajoie et al (2012) may not have found any change in trail limb trajectory as a result of weighting the lead limb because the lead limb trajectory did not change. Our novel tool to measure proprioceptive sense has provided a brief insight into the possible role of lead limb proprioception on trail limb control over an obstacle. Our results suggest that there may be a relationship between lead limb proprioceptive

sense and trail limb trajectory. Although the sample size was small, it appears that people with more disordered lead limb proprioceptive sense are unable to appropriately scale trail limb trajectory when vision is compromised. Future studies should be designed to create a discrepancy between the motor plan set by the visual system and the subsequent updating of that motor plan by proprioception to fully understand this phenomenon.

Do proprioceptive deficits alter the end-point control of the lead and trail limbs?

In the absence of on-line foot regulation (via vision) toe clearance and foot placements become more variable (Patla et al., 2004; Patla and Greig, 2006). The variability in lead toe clearance and foot placement was greater in the OV condition for both the AB and SCI groups. Both groups also modulated variability from FV to OV conditions in a similar manner. The trail limb on the other hand was not so consistently varied. The SCI participants displayed greater variability in trail horizontal distance than the AB group. The AB group also showed little change in toe clearance variability, but larger changes in foot placement variability in the OV conditions. On the other hand, the SCI subjects showed the opposite trend. During the OV condition they increased trail clearance variability, but there was little change in trail foot placement variability. We also observed a slight positive relationship between lead limb proprioceptive sense and the variability in trail toe clearance and, to a lesser extent, with the variability in trail horizontal distance. Our observations would suggest that proprioceptive sense could play a role in the differences seen in the trail limb. This could be plausible as this limb is mostly proprioceptively driven (likely more so in the OV condition) and previous work showed that arm movements in the absence of proprioception become more variable

when vision is unavailable (Sainburg et al., 1993; Bard et al., 1995; Gordon et al., 1995; Sainburg et al., 1995; Guedon et al., 1998)

Modulation of lower limb joint kinematics during obstacle crossing

Both groups (AB and SCI) exhibited an increase in ankle, hip and knee (dorsi)flexion in both the lead and trail limb to cross the obstacle. This observation was expected and consistent with previous work for the AB group (Mcfadyen, 1993), but was not consistent with previous studies in people with SCI (Ladouceur et al., 2003) that showed that individuals with an SCI only increase knee flexion when crossing obstacles and do not increase hip flexion. In our study, the increase in hip flexion to cross the obstacle was robust across all SCI participants. It is plausible that we used greater obstacle heights than Ladoucer et al., increasing the demand for hip flexion by our participants. In able-bodied individuals, an increase in flexion of the joints of the lower limb during obstacle crossing has been attributed to a "knee flexor' strategy (Mcfadyen, 1993). The emergence of an active knee flexor moment, leads to an active increase in knee flexion, as well as passively increasing hip and ankle dorsi(flexion) via intersegmental dynamics. It is possible that the SCI group used this same strategy, however more detailed analysis of lower limb dynamics will be required to investigate this possibility.

When vision was obstructed, different joint kinematic strategies between the SCI and AB group emerged. In the OV condition, there was an increase in lead toe clearance, which was associated with an increase in hip flexion in the AB group whereas the SCI

group demonstrated changes in all of the lower limb joints. Previous work has shown that changes in knee flexion play a critical role in limb elevation over the obstacle, whereas hip flexion plays a greater role in limb progression (Niang and McFadyen, 2004). The AB group demonstrated only a modest increase in lead toe clearance (~4.5%), and so it should not be surprising that there was little modulation of knee flexion. It is possible that the increase in hip flexion in the AB group was associated with the increase in lead horizontal distance from FV to OV conditions, thus requiring a longer stride to clear the obstacle. On the other hand, the SCI participants showed increases in both hip and knee flexion, which could explain the greater increase in lead toe clearance (~25%) as well as the effect on lead horizontal distance (which increased by ~9%).

There were similar changes in trail joint kinematics from the FV to OV condition between the AB and SCI groups. Both groups increased flexion at the ankle, knee and hip. As previously mentioned, AB and SCI individuals increased trail horizontal distance (by ~9% and 12%, respectively) between FV and OV conditions, which should correspond to an increase in all of the ankle, knee and hip angles (McFadyen et al., 1993). However, trail limb clearance was reduced in the AB group (by ~14%) and increased in the SCI group (by ~15%) between FV and OV conditions. For the SCI group an increase in trail clearance height could be attributed to the increase in all trail limb joint angles. For the AB group it was surprising to see an increase in trail knee angle as trail clearance on average decreased during the OV condition for this group.

Limitations

A major limitation in our study is the relatively small sample size, which is frequently a consideration in the SCI literature. To our knowledge this is the largest study to date examining overground obstacle crossing in people with m-iSCI. The majority of research examining obstacle crossing strategies involving able-bodied individuals (Chou and Draganich, 1998b; Mohagheghi et al., 2004; Patla et al., 2004; Patla and Greig, 2006; Rietdyk and Rhea, 2006; Lu et al., 2008; Marigold and Patla, 2008) or individuals with diabetic neuropathy (Liu et al., 2010) and cerebellar damage (Morton et al., 2004; Ilg et al., 2008) have consistently used 7-15 participants. Nevertheless, the results from this study offer some preliminary new insights into the various factors that contribute to the recovery of skilled walking in people with m-iSCI. Moreover, most of our m-iSCI participants were relatively high functioning, and so the results of this study may only be applicable to a relatively small proportion of the m-iSCI population. However, considerations of the factors contributing to skilled walking recovery are likely to be most relevant to individuals who have already recovered basic ambulatory function.

The obstacle-crossing environment we created may not necessarily reflect those encountered in our everyday environments. However, it was critical that we controlled for inter-subject variability in motor deficits by scaling obstacle height. In addition, we used parallel bars to minimize the potential confounding factor of different gait aids required of the SCI subjects. The majority of our SCI subjects used the parallel bars whereas the AB subjects did not. We felt that forcing the AB subjects and some of the SCI subjects to use parallel bars when they normally would not require them would affect

their natural obstacle crossing strategies. For example, it has been shown that haptic feedback from even minimal contact through the hands can lead to increased balance stabilization (Jeka, 1997). Because we wanted to relate individuals' obstacle crossing strategies with their clinical profile, we felt that permitting the most natural (or comfortable) conditions possible was required. In addition, we found that SCI subjects displayed increased toe clearance heights over the obstacle compared to the AB subjects during the OV condition. This suggests that even though SCI participants had increased balance feedback through contact with the parallel bars they still implemented a safety strategy when crossing the obstacle.

We did not consider the effect of the support limb on toe clearance. Obstacle clearance is an end-point control task and slight changes in any of the lower limb joints (swing or stance limb) could alter the toe trajectory of the height (Winter, 1992). Moreover, changes in the horizontal distance of the stance limb has shown to affect the moments created at its joints, possibly having an effect on the end-point trajectory of the swing limb (Chou and Draganich, 1998a) and may have accounted for some differences seen in toe kinematic parameters. Given these factors, our main focus was to understand how toe position and toe clearance changed as a function of vision in people with m-iSCI in comparison to AB individuals. We also maintained the same obstacle height for both conditions thus minimizing the changes in stance limb moments at the hip (Chou and Draganich, 1998a). Moreover, our protocol and outcome measures were consistent with previous studies with similar paradigms. Future studies will allow for more detailed analysis of the kinematics and kinetics of both the stance and swing limbs during obstacle crossing.

We did not control for gait speed. Although, gait speed plays a critical role in joint kinetics during obstacle crossing, changes in gait speed in young and elderly adults during obstacle crossing has been shown not to affect toe clearance values (Draganich and Kuo, 2004). Moreover, if there was a reduction in gait speed during the OV condition we would expect a decrease in both groups (Marigold and Patla, 2008). Perhaps the SCI participants decreased gait speed to a greater extent than AB individuals, however this was not apparent in the joint kinematics, as both groups were very comparable. It is also possible that a decrease in gait speed would lead to a greater number of saccades towards the obstacle given the increased time to cross. However, it seems that gaze behavior is a likely a function of steps (visually sampling one step ahead vs two steps ahead). Moreover, given the impairments in proprioception and level of self-efficacy, this population would presumably have a greater dependency on vision irrespective of speed. Nonetheless changes in gait speed can effect the angular velocities of different limb segments, thus increasing the need to control for intersegmental dynamics (Patla and Prentice, 1995). Future studies will allow for investigating how persons with m-iSCI utilize speed to control gaze behavior and limb kinetics and kinematics.

Clinical Implications and Future Directions

In this study we have shown that persons with m-iSCI, regardless of their motor impairments, can have deficits in proprioceptive sense and that these deficits, along with motor impairments and the associated impacts on balance and ambulation self-efficacy, could lead to alterations in locomotor strategies underlying obstacle crossing and have ramifications for the design of rehabilitation strategies to improve functional ambulation. It is known that proprioception plays a critical role in the control of multi-joint movements, and walking (especially skilled walking) requires intricate coordination across multiple joints. Given the critical role of the sensory system in movement control, it is surprising that very little is know about how sensory deficits in SCI affect walking and their impact on recovery. Most gait rehabilitation studies to-date have focused on basic measures of walking such as the 10-meter walk test and 6-minute walk test. These outcome measures are typically conducted in open spaces with very little obstructions. However, in everyday life, we are constantly required to adapt to different environments and we are only beginning to understand the functional demands required of people with m-iSCI to perform the more skilled walking movements required of everyday situations.

Future studies are required to gain deeper understanding of the multiple factors contributing to the recovery of functional walking in people with SCI, such as the contribution of sensory and motor deficits on the control of inter-segmental limb dynamics during walking and the attentional requirements in people with SCI during skilled walking tasks, such as obstacle crossing. Very little is known about how this populations relies on vision to control movement and we have only examined a small aspect of how this population uses vision during obstacle crossing. Does the SCI population spend time in travel fixation during obstacle crossing or do they focus their gaze on specific 'important' locations in the environment? When asked to step on specific targets how is their gaze behavior altered in comparison to healthy able-bodied individuals and those with impairments in gaze behavior such as older adults at high risk for falls? These questions will be important to understand how this population uses saccades and fixations and whether these strategies are beneficial or detrimental to their

ability to functionally ambulate. Lastly, our ability to quantify proprioceptive sense and identify impairments in proprioception, even in people with SCI who may be considered high-functioning, may make this population a useful model to further understand the role of

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			Height	Weight
ID	Age	Sex	(cm)	(kg)
SCI01	62	М	178	84
SCI02	48	М	188	84
SCI03	37	М	180	84
SCI04	58	F	155	60
SCI05	58	F	145	58
SCI06	32	М	173	80
SCI07	63	М	170	87
SCI08	33	Μ	170	79
SCI09	58	F	156	61
Average	50	6M, 3F	168	75
AB01	40	М	182	89
AB02	28	М	188	100
AB03	48	Μ	183	93
AB04	60	М	175	75
AB05	51	F	152	69
AB06	45	F	175	66
AB07	53	F	155	72
AB08	54	Μ	175	75
AB09	31	М	178	68
AB10	65	F	163	76
Average	48	6M, 4F	173	78

Table 1: Baseline characteristics.

ID	Level of Injury	Chronicity	AIS	LEMS	10 MWT Self Selected (m/s)	10 MWT Max (m/s)	BBS	SCI-FAP Total	ABC	ASCQ	Usual Gait Aids	Used Parallel Bars?
SCI01	C4/5	2	D	35	0.83	1.12	49	13.01	61	60	None	Ν
SCI02	C3,C4/5,C7	4	Е	50	1.14	1.64	56	15.88	91	86	None	Ν
SCI03	C7	21	С	24	0.57	1.00	30	100.47	52	54	Walker	Y
SCI04	L4/5	34	D	42	0.76	0.83	54	40.47	64	54	Walker	Y
SCI05	C5-T2	3	D	42	0.95	1.40	56	16.57	36	31	None	Ν
SCI06	T5-6	12	С	12	0.17	0.22	10	590.76	24	25	Walker	Y
SCI07	T11	1	D	49	0.90	1.29	55	11.90	72	78	Walking Sticks	Y
SCI08	C5/C6	11	С	14	0.11	0.17	25	296.89	20	45	Walker	Y
SCI09	Т3	7	D	27	0.41	0.58	44	78.81	57	56	Forearm Crutches	Y
Average		10.56	3C, 5D, 1E	32.78	0.65	0.92	42	129.42	53	54		

Table 2: Functional assessment scores in participants with an SCI. AIS = ASIA (American Spinal Injury Association (ASIA) Impairment Scale LEMS = Lower Extremity Motor Score

10 MWT = Ten Meter Walk Test

BBS = Berg Balance Scale

SCI-FAP = Spinal Cord Injury Functional Ambulation Profile ABC = Activities-Specific Balance Confidence Questionnaire ASCQ = Ambulatory Self-Confidence Questionnaire



Figure 2: Experimental setup. Participants were situated between parallell bars and asked to step over an obstacle that was positioned in between a doorframe (indicating its spatial location) under full and obstructed vision conditions. Obstacle height was scaled to each person's regular and maximum step height.



Figure 3: Overall proprioceptive sense.

Mean overall static position sense (A) and movement detection threshold (B) are plotted for both AB (white bars) and SCI (black bars) groups. Error bars represent 95% confidence intervals

* Significant group differences are represented by a horizontal bar with an asterisk.



Figure 4: Toe clearance as a percentage of maximum step height. Mean lead (left) and trail (right) toe clearance height is plotted as a percentage of maximum step height in both the obstrued (black dots) and full (white dots) vision conditions for each subject. FV = Full Vision OV = Obstructed Vision



Figure 5: Relationship between lower limb muscle strength and toe clearance height.

Mean toe clearance (normalized to obstacle height) is plotted against lower limb muscle strength (examined by the LEMS) for the lead (left) and trail (right) limbs in both obstructed (black dots) and full (white dots) vision conditions for each SCI subject.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.

LEMS = Lower Extremity Motor Score

FV = Full Vision

OV = Obstructed Vision



Figure 6: Gaze behaviour.

Mean number of saccades towards the obstacle during the two and one strides before crossing and during the step over the obstacle is plotted for both groups (A), in addition to mean values for the total number of saccades (B) and total gaze durations (C) for AB and SCI subjects. All error bars represent 95% confidence intervals.



Figure 7: Relationship between gaze behaviour and overall proprioceptive sense.

Total number of saccades (A) and mean fixation duration (B) against overall proprioceptive sense (static position sense (left) and movement detection threshold (right)) is plotted for each SCI subject. Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound

95% confidence interval.



Figure 8: Relationship between the number of saccades towards the obstacle in the strides prior to obstacle crossing and overall proprioceptive sense.

Number of saccades in the two strides (A) and one stride (B) prior to crossing the obstacle against overall proprioceptive sense (static position sense (left) and movement detection threshold (right)) is plotted for each SCI subject. Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.



Figure 9: Relationship between self-confidence and gaze behaviour.

Total number of saccades (A) and mean fixation duration (B) is plotted against ASCQ (left) and ABC (right) scores for each SCI subject. Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound

95% confidence interval. ASCQ = Ambulatory Self-Confidence Questionnaire

ABC = Activities-Specific Balance Confidence Questionnaire





The number of obstacle hits by the lead (A) and trail (B) limbs in both the obstructed (black bars) and full vision (gray bars) conditions are depicted for each individual subject. FV = Full Vision OV = Obstructed Vision





Lead limb joint kinematics (A-C) and lead limb vertical toe trajectory (D) from representative AB (left) and SCI subjects (right) during unobstructed and obstructed walking. FV = Full Vision OV = Obstructed Vision





Trail limb joint kinematics (A-C) and trail limb vertical toe trajectory (D) from representative AB (left) and SCI subjects (right) during unobstructed and obstructed walking. FV = Full Vision OV = Obstructed Vision



Trail Limb



Figure 13: Mean toe kinematics during obstacle crossing.

Normalized lead (left) and trail (right) limb mean toe clearance (A) and mean horizontal distance (B) are plotted for both AB (white dots) and SCI (black dots) groups in both conditions. Error bars represent 95% confidence intervals.

* Main effect of condition is represented by a horizontal bar with an asterisk.

FV: Full Vision

OV = Obstructed Vision

Trail Toe Clearance





Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.

Trail Toe Clearance



Figure 15: Relationship between trail limb proprioceptive sense and trail limb toe kinematics.

Mean change scores (difference between obstructed vision and full vision) in trail toe clearance (A) and trail horizontal distance (B) is plotted against trail limb static position sense (left) and trail limb movement detection threshold (right) for each SCI subject.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.

Lead Toe Clearance



Figure 16: Relationship between lead limb proprioceptive sense and lead limb toe kinematics.

Mean change scores (difference between obstructed vision and full vision) in lead toe clearance (A) and

lead horizontal distance (B) is plotted against lead limb static position sense (left) and lead limb movement detection threshold (right) for each SCI subject.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.





Mean variability in lead (left) and trail (right) toe clearance (A) and horizontal distance (B) are plotted for AB (white dots) and SCI (black dots) groups in both conditions. Error bars represent 95% confidence intervals. * Main effect of condition is represented by horziontal bars with an asterisks.

* Main effect of group is represented by a vertical bar with an asterisk.

FV: Full Vision

OV = Obstructed Vision

Trail Toe Clearance Variability



Trail Horizontal Distance Variability



Lead Static Position Sense

Lead Movement Detection Score

(absolute error)



Mean change scores (difference between obstructed vision and full vision) in trail toe clearance variability (A) and trail horizontal distance variability (B) are plotted against lead limb static position sense (left) and lead limb movement detection threshold (right) for each SCI participant.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.

Trail Toe Clearance Variability



Trail Horizontal Distance Variability



(absolute error)



Mean change scores (difference between obstructed vision and full vision) in trail toe clearance variability (A) and trail horizontal distance (B) are plotted against trail limb static position sense (left) and trail limb movement detection threshold (right) for each SCI subject.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.

Lead Toe Clearance Variability



Lead Horizontal Distance Variability



(absolute error)

Figure 20: Relationship between lead limb proprioceptive sense and variability (coefficient of variability) in lead limb toe kinematics.

Mean change scores (difference between obstructed vision and full vision) in lead toe clearance variability (A) and lead horizontal distance variability (B) are plotted against lead limb static position sense (left) and lead limb movement detection threshold (right) for each SCI subject.

Pearson's correlation coefficient (r) values are reported in the insert text of each scatterplot. Values in parentheses are the lower and upper-bound 95% confidence interval.





Black vertical bars represent mean peak lead ankle (A), knee (B) and hip (C) (dorsi)flexion for both AB (left) and SCI (right) groups during baseline unobstructed walking, and obstacle crossing under full vision and obstructed vision conditions. Gray lines represent individual subject data for each condition. * Horizontal bars with asterisks represent main effects of condition.

FV = Full Vision

OV = Obtsructed Vision



Figure 22: Peak trail limb joint angles.

Black vertical bars represent mean trail peak ankle (A), knee (B) and hip (C) dorsi(flexion) for both AB (left) and SCI (right) groups during baseline unobstructed walking, and obstacle crossing under full vision and obstructed vision conditions. Gray lines represent individual subject data for each condition.

* Horizontal bars with asterisks represent main effects of condition.

FV = Full Vision OV = Obtsructed Vision





Appendix A



This form may be copied freely but should not be altered without permission from the American Spinal Injury Association.

Muscle Function Grading

 $\bm{0}=\text{total paralysis}$

1 = palpable or visible contraction

 ${\bm 2} = {\rm active \ movement, \ full \ range \ of \ motion \ (ROM) \ with \ gravity \ eliminated}$

 $\mathbf{3} = \text{active movement, full ROM against gravity}$

 $\bm{4}=$ active movement, full ROM against gravity and moderate resistance in a muscle specific position.

5 = (normal) active movement, full ROM against gravity and full resistance in a functional muscle position expected from an otherwise unimpaired person.

 ${\bf 5^{\star}} = (\text{normal}) \text{ active movement, full ROM against gravity and sufficient resistance to be considered normal if identified inhibiting factors (i.e. pain, disuse) were not present.$

 \mathbf{NT} = not testable (i.e. due to immobilization, severe pain such that the patient cannot be graded, amputation of limb, or contracture of > 50% of the normal range of motion).

Sensory Grading

 $\mathbf{0} = \mathsf{Absent}$

 $\label{eq:last_last} 1 = \mbox{Altered, either decreased/impaired sensation or hypersensitivity}$

- 2 = Normal
- $\mathbf{NT} = \mathrm{Not} \ \mathrm{testable}$

Non Key Muscle Functions (optional)

May be used to assign a motor level to differentiate AIS B vs	. C
Movement	Root level
Shoulder: Flexion, extension, abduction, adduction, internal and external rotation Elbow: Supination	C5
Elbow: Pronation Wrist: Flexion	C6
Finger: Flexion at proximal joint, extension. Thumb: Flexion, extension and abduction in plane of thumb	C7
Finger: Flexion at MCP joint Thumb: Opposition, adduction and abduction perpendicular to palm	C8
Finger: Abduction of the index finger	T1
Hip: Adduction	L2
Hip: External rotation	L3
Hip: Extension, abduction, internal rotation Knee: Revion Ankle: Investion and eversion Toe: MP and IP extension	L4
Hallux and Toe: DIP and PIP flexion and abduction	L5
Hallux: Adduction	S1

ASIA Impairment Scale (AIS)

A = Complete. No sensory or motor function is preserved in the sacral segments S4-5.

B=Sensory Incomplete. Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-5 (light touch or pin prick at S4-5 or deep anal pressure) AND on motor function is preserved more than three levels below the motor level on either side of the body.

 $\label{eq:constraint} \begin{array}{l} \textbf{C} = \textbf{Motor Incomplete.} \mbox{ Motor function is preserved below} \\ the neurological level*, and more than half of key muscle functions below the neurological level of injury (NLI) have a muscle grade less than 3 (Grades 0-2). \end{array}$

$$\label{eq:D} \begin{split} \textbf{D} &= \textbf{Motor Incomplete.} \ \text{Motor function is preserved below} \\ \text{the neurological level}^{**}, \text{ and } \underline{at \ \text{least half}} \ (half \ or \ more) \ of \ key \\ \text{muscle functions below the NLI have a muscle grade} \geq 3. \end{split}$$

E = Normal. If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without an initial SCI does not receive an AIS grade.

** For an individual to receive a grade of C or D, i.e. motor incomplete status, they must have either (1) voluntary and sphincter contraction or (2) scace asressory sparing <u>uity</u> sparing or mitor furtility of more than three levels below the motor level for that side of the body. The International Standards at this time allows even non-key muscle function more than 3 levels below the motor level to be used in determining motor incomplete status (AIS B versus C).

NOTE: When assessing the extent of motor sparing below the level for distinguishing between AIS B and C, the motor level on each side is used; whereas to differentiate between AIS C and D (based on proportion of key muscle functions with strength grade 3 or greater) the neurological level of injury is used.



CLASSIFICATION OF SPINAL CORD INJURY



Steps in Classification

The following order is recommended for determining the classification of individuals with SCI.

1. Determine sensory levels for right and left sides.

The sensory level is the most caudal, intact dermatome for both pin prick and light touch sensation.

2. Determine motor levels for right and left sides.

Defined by the lowest key muscle function that has a grade of at least 3 (on supine testing), providing the key muscle functions represented by segments above that level are judged to be intact (graded as a 5). Note: in regions where there is no myotome to test, the motor level is presumed to be the same as the sensory level, if testable motor function above that level is also normal.

3. Determine the neurological level of injury (NLI)

This refers to the most caudal segment of the cord with intact sensation and antigravity (3 or more) muscle function strength, provided that there is normal (intact) sensory and motor function rostrally respectively. The NLI is the most cephalad of the sensory and motor levels determined in steps 1 and 2.

4. Determine whether the injury is Complete or Incomplete.

(i.e. absence or presence of sacral sparing) If voluntary anal contraction – **No** AND all S4-5 sensory scores = **0** AND deep anal pressure – **No**, then injury is **Complete**. Otherwise, injury is **Incomplete**.

5. Determine ASIA Impairment Scale (AIS) Grade:



Is injury Motor Complete? If YES, AIS=B

NO (No=voluntary anal contraction OR motor function more than three levels below the motor level on a given side, if the patient has sensory incomplete classification)

Are <u>at least</u> half (half or more) of the key muscles below the <u>neurological</u> level of injury graded 3 or better?



If sensation and motor function is normal in all segments, AIS=E

Note: AIS E is used in follow-up testing when an individual with a documented SCI has recovered normal function. If at initial testing no deficits are found, the individual is neurologically intact; the ASIA Impairment Scale does not apply.

Appendix B

Appendix

The Spinal Cord Injury Functional Ambulation Profile (SCI-FAP)

The SCI-FAP is composed of 7 tasks: (1) Carpet, (2) Up & Go, (3) Obstacles, (4) Stairs, (5) Carry, (6) Step, and (7) Door. Each participant is given a rest period between tasks long enough for the tester to explain and demonstrate the next task. Each participant is instructed to use an assistive device and/or brace(s) as needed. The tester provides instructions and answers the participant's questions. The tester provides physical assistance if needed. The tester times the participant during each task. The tester walks behind the subject, not beside, to prevent affecting the participant's speed. The tester provides feedback/encouragement only after the task is completed. The tester records the performance time for all 7 tasks on a data collection form (see scoring table below). If the participant task, and an assistance rating of 6 ('unable to complete') (see scoring table below). If the participant task longer than the maximum time to complete a task, he/she is assigned the maximum time, and the assistance rating that corresponds to the devices/assistance used for that task. Upon completion of all tasks, the tester calculates a total SCI-FAP score (see Scoring the Spinal Cord Injury Functional Ambulation Profile below).

Introduction

The tester provides an explanatory overview of the 7 tasks comprising the SCI-FAP. Prior to performance of each task, the tester explains and demonstrates the task. The participant is informed that performance of each task is timed and is instructed to ask for clarification at any time.

Although dimensions of the chair, obstacles, stairs, door, step, and bag have been described specifically, items having similar dimensions may be used, provided that the dimensions are noted and reproduced on subsequent testing.

1) Carpet Max time: 220 seconds

Setup: Carpeted area or a piece of short pile carpet, no less than 7-m long and 2-m wide, securely taped to the floor. Starting point is marked with a 1-m strip of masking tape. End point is marked exactly 5-m from the starting point with a 2-cm piece of masking tape. Both starting point and end point are at least 1-m from the edge of the carpet.

- 1. Tester explains while demonstrating the Carpet task: "When I say 'go,' walk at your normal, comfortable pace until I say 'stop.' "
- 2. Tester assists participant as needed in placing toes on starting line tape.
- 3. Tester says "go," and presses stopwatch to begin timing.
- Participant walks toward the end point. Tester walks alongside the participant as the participant traverses the 5-m distance.
- Tester presses stopwatch to stop timing once both of the participant's feet have crossed the end point. Tester tells the participant to stop when he or she is beyond the end point.
- 6. Tester records time on data collection form.

2) Up & Go Max time: 455 seconds

Setup: Standard armchair with a 44-cm seat height (from floor) is placed on the hard, non-carpeted floor. Three meters away, a 1-m strip of masking tape is placed on the floor.



- 1. Tester explains while demonstrating the Up & Go task: "You will sit in this chair with your back against the back of the chair and your arms resting on the armrests. When I say 'go,' you will stand up from the chair, walk at your normal comfortable pace past this line, turn around, walk back to the chair, and sit down, making sure your back is against the back of the chair."
- 2 Participant assumes sitting position in the chair. Tester stands beside the chair and prepares to walk with the participant.
- 3 Tester says "go," and presses stopwatch to begin timing.
- 4. Tester monitors line to ensure both of participant's feet cross the line before turning around.
- 5. Tester stops timing when participant is fully seated with back against the chair.
- 6. Tester records time on data collection form.

3) Obstacles* Max time: 570 seconds

Setup: A 1-m piece of masking tape is placed on a hard, non-carpeted floor to mark the starting point. A standard brick is placed on the floor at the 1.5-m mark and the 3-m mark. A trash can (diameter 56cm, height 70cm) is placed at the 5-m mark.



- 1. Tester explains while demonstrating the Obstacles task: "When I say 'go,' walk forward at your normal, comfortable pace and step over each brick. Then, walk around the trash can from either the left or right. Then walk back stepping over the bricks again. Do not hit the bricks or bin with your body or walking aid, if possible. Continue walking until I say 'stop." Tester assists participant as needed in placing toes on starting line. 2
- 3
- Tester says "go," and presses stopwatch to begin timing.
- 4. Tester walks with participant.
- When both of the participant's feet have crossed the end line, tester presses stopwatch to stop 5. timing. Tester tells the participant to "stop" when he or she is beyond the end line. 6
- Tester records time on data collection form.

* If the participant hits one or more of the obstacles with his/her body or walking aid, 1 is added to the factor chosen for this task (e.g., if participant completed task with '1 cane/crutch' - a factor of 2, but he/she hits 1 or more obstacles, he/she is assigned a factor of 3).

4) Stairs* Max time: 310 seconds

Setup: Stairs with 4 steps, hand railings on both sides, and the following measurements are utilized: 29-cm stair depth, 76-cm stair width, 15-cm stair height, 76-cm platform depth, and 76-cm platform width. A 1-m piece of masking tape is placed 25 cm from the base of the first step.



- 1. Tester explains while demonstrating the Stairs task: "When I say 'go,' walk up the stairs at your normal, comfortable pace to the top of the stairs, turn around, and come back down. You may use the handrails if needed, but try to use them as little as possible.
- 2 Tester assists participant as needed in placing toes on starting line.
- 3. Tester says "go," and presses stopwatch to begin timing.
- Tester follows participant up stairs to guard. 4
- Tester presses stopwatch to stop timing when both of the participant's feet are in firm contact 5. with the floor
- Tester records time on data collection form. 6

*Participant may use any technique to ascend and descend stairs (i.e., forwards, backwards, sideways), but must turn around at the top of the stairs so that he/she approaches the descent from the forwards direction. The technique used is recorded under the "Comments" section of the scoring form.

Max time: 220 seconds 5) Carry

Setup: A 1-m strip of masking tape is placed on the hard, non-carpeted floor at the starting point. Five meters ahead of the starting point, a 2-cm piece of masking tape marks the end point. A shoulder bag, 36cm long, 24-cm wide and 16-cm deep with a 5-lb weight placed inside, is worn by the participant. The shoulder strap should measure 4-cm in width, is adjusted so that the top of the bag is at the level of the iliac crest. The bag should hang across the participant's body so that if the bag is over the left shoulder it would hang on the right side of the participant's torso. The bag should hang either in front, beside, or behind the participant's torso while the participant is ambulating, according to the participant's preference. The position of the bag must be documented (under the "Comments" section of the scoring form) so that this may be replicated during subsequent trials.

- Tester explains while demonstrating the Carry task: "When I say 'go' walk at your normal, 1. comfortable pace, while carrying this bag over either shoulder, until I say 'stop'.
- 2 Tester assists the participant as needed in placing toes on the starting line, and can assist in placing the bag over either of the participant's shoulders. 3
 - Tester says "go" and presses stopwatch to begin timing.
- 4. Participant walks toward the end point. Tester walks alongside the participant as the participant traverses the 5-m distance.
- Tester presses stopwatch to stop timing once both of the participant's feet have crossed the 5. end point. Tester tells participant to stop when he or she is beyond the end point.
- 6. Tester records time on data collection form.

Max time: 185 seconds 6) Step

Setup: A step with the measurements shown in the diagram below is used. Two pieces of masking tape are placed on the floor to indicate the start and finish points. The first, 1-m in length, is placed 1-m in front of the step. The second piece, 2-cm in length, is placed 1-m behind the step. 122cm



- Tester explains while demonstrating the Step task: "When I say 'go', walk towards the step, up and over, and continue walking until I say stop."
- 2. Tester assists participant as needed in placing toes on the starting point.
- 3. Tester says "go" and presses stopwatch to begin timing.
- Participant walks toward the end point. Tester follows participant through the task for safety.
 Tester presses stopwatch to stop timing when both of the participant's feet have crossed the
- end point.
- 6. Tester records time on data collection form.

7) Door Max time: 250 seconds

Setup: A wooden door with a latch handle, non-spring loaded, with the following measurements: 4-cm door depth, 95-cm door width, and 211-cm door height (see diagram below). The floor should be the same hard, non-carpeted surface on both sides of the door with no breaks or rises. The starting point is a 1-m strip of masking tape, which is placed on the floor 1.5-m from the door. Three meters ahead of the starting point, a 2-cm piece of masking tape marks the finish point.



- Tester explains while demonstrating the Door task: "When I say 'go', walk forwards at your normal, comfortable pace, **pull*** open and go through the door, leave the door open, and walk to the end point". Note: participants can use any method they normally use to open the door.
- 2. Tester assists participant as needed in placing toes on the starting point.
- 3. Tester says "go" and presses stopwatch to begin timing.
- 4. Tester follows participant through the door for safety.
- Tester presses stopwatch to stop timing when both of the participant's feet have crossed the end point.
- 6. Tester records time on data collection form.

*Participant may use any part of his/her own body or walking aid to open the door. This will not be considered any differently in the scoring. The method of door opening is recorded under the "Comments" section of the scoring form.

- Scoring the Spinal Cord Injury Functional Ambulation Profile
 1) Tester multiplies time recorded for each task by appropriate assistance rating (see below) according to assistive device or assistance required during that task, and records the total in the appropriate cell in Row D.
 - 2) Tester divides the number calculated in Row D by the mean time of able-bodied individuals (Row E).
 - Tester sums the 7 task scores to obtain the total SCI-FAP score.

Task (max time)	Carpet (220s)	Up&Go (455s)	Obstacles (570s)	Stairs (310s)	Carry (220s)	Step (185s)	Door (250s)
A. Time							
B. Assistance							
C. Hit Obstacle (+1)	/	/		/	/	/	/
$\mathbf{D} = \mathbf{A} \mathbf{x} \left(\mathbf{B} + \mathbf{C} \right)$							
Е.	4.4	9.1	11.4	6.2	4.4	3.7	5.0
Task Total = D/E							

Total SCI-FAP score =

Assistance

1 = independent

2 = 1 cane/crutch/rail

3 = 2 canes/crutches/rails

4 = walker

5 = assist of 1

6 = unable to complete

Independent refers to walking without any walking aids or assistance. Walker refers to standard walker or 2- or 4-wheeled walker; assist of 1 refers to physical assistance of 1 person whether minimum, moderate or maximum assist.

Comments
Carpet
Up & Go
Obstacles
Stairs
Carry
Step
Door

6

Appendix C

Berg Balance Scale

The Berg Balance Scale (BBS) was developed to measure balance among older people with impairment in balance function by assessing the performance of functional tasks. It is a valid instrument used for evaluation of the effectiveness of interventions and for quantitative descriptions of function in clinical practice and research. The BBS has been evaluated in several reliability studies. A recent study of the BBS, which was completed in Finland, indicates that a change of eight (8) BBS points is required to reveal a genuine change in function between two assessments among older people who are dependent in ADL and living in residential care facilities.

Description:

14-item scale designed to measure balance of the older adult in a clinical setting.

Equipment needed: Ruler, two standard chairs (one with arm rests, one without), footstool or step, stopwatch or wristwatch, 15 ft walkway

Completion:

<u>Time:</u> <u>Scoring:</u>	15-20 minutes A five-point scale, ranging from 0-4. "0" indicates the lowest level of function and "4" the highest level of function. Total Score = 56
Interpretation:	41-56 = low fall risk 21-40 = medium fall risk 0 –20 = high fall risk

A change of 8 points is required to reveal a genuine change in function between 2 assessments.

Berg Balance Scale

Name:	Date:
Location:	Rater:
ITEM DESCRIPTION	SCORE (0-4)
Sitting to standing Standing unsupported Sitting unsupported Standing to sitting Transfers Standing with eyes closed Standing with feet together Reaching forward with outstretched arm Retrieving object from floor Turning to look behind Turning 360 degrees Placing alternate foot on stool Standing with one foot in front Standing on one foot	
standing on one root	

Total

GENERAL INSTRUCTIONS

Please document each task and/or give instructions as written. When scoring, please <u>record the</u> <u>lowest response category that applies</u> for each item.

In most items, the subject is asked to maintain a given position for a specific time. Progressively more points are deducted if:

- the time or distance requirements are not met
- the subject's performance warrants supervision
- the subject touches an external support or receives assistance from the examiner

Subject should understand that they must maintain their balance while attempting the tasks. The choices of which leg to stand on or how far to reach are left to the subject. Poor judgment will adversely influence the performance and the scoring.

Equipment required for testing is a stopwatch or watch with a second hand, and a ruler or other indicator of 2, 5, and 10 inches. Chairs used during testing should be a reasonable height. Either a step or a stool of average step height may be used for item # 12.
Berg Balance Scale

SITTING TO STANDING INSTRUCTIONS: Please stand up. Try not to use your hand for support. () 4 able to stand without using hands and stabilize independently

-)4
- able to stand independently using hands able to stand using hands after several tries ()2
- () | () 0 needs minimal aid to stand or stabilize
- needs moderate or maximal assist to stand

STANDING UNSUPPORTED

INSTRUCTIONS: Please stand for two minutes without holding on.

- able to stand safely for 2 minutes able to stand 2 minutes with supervision ()4 ()3
- ()2 ()1 able to stand 30 seconds unsupported needs several tries to stand 30 seconds unsupported
- () 0 unable to stand 30 seconds unsupported

If a subject is able to stand 2 minutes unsupported, score full points for sitting unsupported. Proceed to item #4.

SITTING WITH BACK UNSUPPORTED BUT FEET SUPPORTED ON FLOOR OR ON A STOOL

INSTRUCTIONS: Please sit with arms folded for 2 minutes.

- able to sit safely and securely for 2 minutes able to sit 2 minutes under supervision
-)4)3)2 able to able to sit 30 seconds
- able to sit 10 seconds
- ()0 unable to sit without support 10 seconds
- STANDING TO SITTING
- INSTRUCTIONS: Please sit down.
- ()4 ()3 ()2 sits safely with minimal use of hands
- controls descent by using hands uses back of legs against chair to control descent
- sits independently but has uncontrolled descent
- ()| needs assist to sit

TRANSFERS

()0

INSTRUCTIONS: Arrange chair(s) for pivot transfer. Ask subject to transfer one way toward a seat with armrests and one way toward a seat without armrests. You may use two chairs (one with and one without armrests) or a bed and a chair.

- able to transfer safely with minor use of hands able to transfer safely definite need of hands) 4
- () 3() 2
- able to transfer with verbal cuing and/or supervision
- needs one person to assist () | () 0
- needs two people to assist or supervise to be safe

STANDING UNSUPPORTED WITH EYES CLOSED

INSTRUCTIONS: Please close your eyes and stand still for 10 seconds.
 () 4 able to stand 10 seconds safely
 () 3 able to stand 10 seconds with supervision

-) 2 able to stand 3 seconds
- unable to keep eyes closed 3 seconds but stays safely
- needs help to keep from falling

STANDING UNSUPPORTED WITH FEET TOGETHER

- INSTRUCTIONS: Place your feet together and stand without holding on. () 4 able to place feet together independently and stand I minute safely
- able to place feet together independently and stand Timinte safety able to place feet together independently and stand I minute with supervision able to place feet together independently but unable to hold for 30 seconds needs help to attain position but able to stand 15 seconds feet together needs help to attain position and unable to hold for 15 seconds)3)2
- ()I ()0

Berg Balance Scale continued...

REACHING FORWARD WITH OUTSTRETCHED ARM WHILE STANDING

INSTRUCTIONS: Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can. (Examiner places a ruler at the end of fingerips when arm is at 90 degrees. Fingers should not touch the ruler while reaching forward. The recorded measure is the distance forward that the fingers reach while the subject is in the most forward lean position. When possible, ask subject to use both arms when reaching to avoid rotation of the trunk.)

- ()4 can reach forward confidently 25 cm (10 inches)
- can reach forward 12 cm (5 inches) can reach forward 5 cm (2 inches) ý 3
- 12
- reaches forward but needs supervision
- ()0 loses balance while trying/requires external support

PICK UP OBJECT FROM THE FLOOR FROM A STANDING POSITION

- INSTRUCTIONS: Pick up the shoe/slipper, which is in front of your feet.

 () 4
 able to pick up slipper safely and easily

 () 3
 able to pick up slipper but needs supervision

 () 2
 unable to pick up but reaches 2-5 cm(1-2 inches) from slipper and keeps balance independently
- unable to pick up and needs supervision while trying unable to try/needs assist to keep from losing balance or falling 11
- ίíο

TURNING TO LOOK BEHIND OVER LEFT AND RIGHT SHOULDERS WHILE STANDING

INSTRUCTIONS: Turn to look directly behind you over toward the left shoulder. Repeat to the right. (Examiner may pick an object to look at directly behind the subject to encourage a better twist turn.)

- looks behind from both sides and weight shifts well looks behind one side only other side shows less weight shift) 4
- ý3
- 12 turns sideways only but maintains balance needs supervision when turning
- needs assist to keep from losing balance or falling ()0

TURN 360 DEGREES

INSTRUCTIONS: Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.
 4 able to turn 360 degrees safely in 4 seconds or less

- ý 3 able to turn 360 degrees safely one side only 4 seconds or less able to turn 360 degrees safely but slowly
-) 2
- needs close supervision or verbal cuing needs assistance while turning ()0

PLACE ALTERNATE FOOT ON STEP OR STOOL WHILE STANDING UNSUPPORTED

INSTRUCTIONS: Place each foot alternately on the step/stool. Continue until each foot has touched the step/stool four times. () 4 able to stand independently and safely and complete 8 steps in 20 seconds

- 13
- able to stand independently and complete 8 steps in > 20 seconds able to complete 4 steps without aid with supervision ()2
- Śт able to complete > 2 steps needs minimal assist
- () O needs assistance to keep from falling/unable to try

STANDING UNSUPPORTED ONE FOOT IN FRONT INSTRUCTIONS: (DEMONSTRATE TO SUBJECT) Place one foot directly in front of the other. If you feel that you cannot place your foot directly in front, try to step far enough ahead that the heel of your forward foot is ahead of the toes of the other foot. (To score 3 points, the length of the step should exceed the length of the other foot and the width of the stance should approximate the subject's normal stride width.)

- able to place foot tandem independently and hold 30 seconds) 4 13
- able to place foot ahead independently and hold 30 seconds
- able to take small step independently and hold 30 seconds needs help to step but can hold 15 seconds loses balance while stepping or standing) 2
- ()0

STANDING ON ONE LEG

INSTRUCTIONS: Stand on one leg as long as you can without holding on. () 4 able to lift leg independently and hold > 10 seconds

ý 3

- able to lift leg independently and hold 5-10 seconds able to lift leg independently and hold \geq 3 seconds $()^{2}$
- tries to lift leg unable to hold 3 seconds but remains standing independently. unable to try of needs assist to prevent fall
- () ()0

() TOTAL SCORE (Maximum = 56)

Appendix D

The Activities-specific Balance Confidence (ABC) Scale*

Instructions to Participants:

For each of the following, please indicate your level of confidence in doing the activity without losing your balance or becoming unsteady from choosing one of the percentage points on the scale form 0% to 100%. If you do not currently do the activity in question, try and imagine how confident you would be if you had to do the activity. If you normally use a walking aid to do the activity or hold onto someone, rate your confidence as it you were using these supports. If you have any questions about answering any of these items, please ask the administrator.

The Activities-specific Balance Confidence (ABC) Scale*

For <u>each</u> of the following activities, please indicate your level of selfconfidence by choosing a corresponding number from the following rating scale:

0%	10	20	30	40	50	60	70	80	90	100%	
no c	onfid	ence					completely confident				

"How confident are you that you will <u>not</u> lose your balance or become unsteady when you...

- 1. ...walk around the house? %
- 2. ...walk up or down stairs? ____%
- 3. ... bend over and pick up a slipper from the front of a closet floor %
- 4. ...reach for a small can off a shelf at eye level? %
- 5. ...stand on your tiptoes and reach for something above your head? %
- 6. ...stand on a chair and reach for something? %
- 7. ...sweep the floor? ____%
- 8. ...walk outside the house to a car parked in the driveway? ____%
- 9. ...get into or out of a car? ____%
- 10. ...walk across a parking lot to the mall? ____%
- 11. ...walk up or down a ramp? ____%
- 12. ...walk in a crowded mall where people rapidly walk past you? ____%

13. ... are bumped into by people as you walk through the mall? ____%

14. ... step onto or off an escalator while you are holding onto a railing? $\frac{\%}{6}$

15. ... step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing? %

16. ...walk outside on icy sidewalks? ____%

^{*}Powell, LE & Myers AM. The Activities-specific Balance Confidence (ABC) Scale. J Gerontol Med Sci 1995; 50(1): M28-34

Appendix E

Appendix III: The ASCQ – Version 3

The Ambulatory Self-Confidence Questionnaire (ASCQ)

This questionnaire measures how confident you are in your ability to walk. If you normally walk with a walker or cane, assume you have your walking aid with you when answering each question. Please answer all items. If activities do not apply to you please guess how you would feel to perform the activity.



____q. use an escalator ?

r. use a moving sidewalk (one at an airport)?

s. walk on a moving bus?

_t. walk from one room to another in your home?

u. walk a short distance without stopping: for example from your home to a car?

v. walk a long distance without stopping: for example from your home to a bus stop?

95