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The Relationship of Plantar Sensation with Standing Balance and Gait Post-Stroke

Stephen Parsons  
*The University of Western Ontario*

Supervisor  
Kara Patterson  
*The University of Western Ontario*

Graduate Program in Health and Rehabilitation Sciences

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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THE RELATIONSHIP OF PLANTAR SENSATION WITH STANDING BALANCE AND GAIT POST-STROKE

(Thesis format: Monograph)

by

Stephen L Parsons

Graduate Program in Health and Rehabilitation Science

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

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Abstract

Gait and balance dysfunction after stroke limit independence and quality of life. Numerous contributing factors have been investigated but the role of sensation deficits has received little attention. This thesis investigated the relationship between plantar cutaneous sensation and 1) standing balance, 2) gait, and 3) use of vision to compensate for sensory loss with a secondary analysis of data from individuals with subacute stroke. Associations between standing balance, gait and sensation were investigated with Spearman correlations. Individuals classified as impaired or intact sensation were compared on gait and standing balance measures. This thesis found plantar sensation is related to standing balance but not spatiotemporal gait parameters. Individuals with impaired sensation were not more likely to employ vision as a compensatory strategy. These results suggest plantar sensation should be addressed during post-stroke rehabilitation of standing balance. Future work should investigate changes in cutaneous sensation with recovery of balance and gait post-stroke.

Keywords

Stroke, Balance, Postural Control, Centre of Pressure, Gait Velocity, Gait Symmetry, Weight Bearing, Romberg Quotient, Sensation, Cutaneous Sensation.
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Chapter 1

1 Introduction

Stroke is very prevalent and is the leading cause of neurological disability in adults (Bohannon, 1987), and affects many aspects of independence including ADLs, mobility and communication.

Gait and balance are two important functions for independent mobility post-stroke. Stroke deficits can vary person to person, so a comprehensive understanding of all of the factors that affect gait and balance is extremely important.

There are many known deficits post-stroke that affect gait and balance. These can include, but are not limited to: impaired proprioception, muscle weakness, spasticity, and weight-bearing symmetry (Hsu, Tang, & Jan, 2003; Lamontagne, Malouin, & Richards, 2001; Lin, 2005; Mansfield, Danells, Zettel, Black, & McIlroy, 2013; Niam, Cheung, Sullivan, Kent, & Gu, 1999). Though there has been extensive research into these impairments, a better understanding of the relationship of between these deficits and functional ability post-stroke is needed. There are still gaps that exist in the knowledge of how specific impairments act on one another and recover over the course of rehabilitation. When many individuals post-stroke still finish rehabilitation with deficient gait and/or balance (Jorgensen, Nakayama, Raaschou, & Olsen, 1995), it suggests that other factors that are not currently known may have been present. Therefore, it is important to further the knowledge of deficits affecting balance and gait to adequately create comprehensive and individual rehabilitation programs.
Sensation has been shown to affect various aspects of gait and balance, though this has been found in populations with peripheral neuropathy or in those who have had artificially reduced sensation. These relationships have not been investigated to a great extent in stroke; only speculation exists currently on the effect of sensory deficits on post-stroke gait and balance.

The main topic of this thesis is plantar cutaneous sensation and its relationship to post-stroke impairments of mobility. Specifically, it will investigate impaired plantar sensation’s relationship to 1) gait, 2) balance, and 3) the utilization of vision in compensating for postural control.

1.1 Stroke

Stroke is the leading cause of neurological disability in adults (Bohannon, 1987) and can present with a number of deficits, dependent on location and severity of the stroke. There are an estimated 50,000 strokes every year in Canada (Hakim, Silver, & Hodgson, 1998) which cost the economy 3.6 billion dollars for physician services, lost wages and hospital costs (Dai et al., 2009). There are roughly 315,000 people living with the effects of stroke in Canada (PHAC, 2011). Disabilities from stroke can affect many aspects of independence including activities of daily living (ADLs), mobility and communication.

Understanding the impairments and disability associated with stroke is becoming a major priority as a large portion of the population is shifting into the “over 65” age category and the risk and incidence of stroke increases with age (Di Carlo et al., 2000).
This may lead to a less independent population as a greater number of strokes occur. Information about stroke related impairments and disability can be used to inform current stroke rehabilitation practices, as well as inform and direct the development of new interventions for stroke. Rehabilitation programs that are tailored to patient-specific deficits are preferred and believed to be more effective than general rehabilitation interventions applied to all patients with stroke (Lindsay, Gubitz, Bayley, & Phillips, 2013).

Gait and balance are two essential functions needed for independence in mobility after stroke. Although they are frequently measured with distinct tests/scales there is also recognition that they are interdependent functions. Michael, Allen and Macko (2005) described the need to determine what factors influence balance to better describe deficits in gait and ambulation, as their study found that scores on the Berg Balance scale – a functional balance assessment – are directly related to the number of steps taken per day.

1.2 Gait after Stroke

The most often stated goal of rehabilitation is to improve gait function (Bohannon, 1987). The recovery of independent mobility is important for improving activities of daily life (Schmid et al., 2007). It has been reported that only 23-37% of stroke patients are able to walk independently in the acute stages (1-7 days), and 50-80% regain independent mobility after 3 weeks (Olney & Richards, 1996). However it is believed that using only the criteria of ‘independence’ for gait (defined as the ability to
walk without assistance from another individual) may underestimate the impact stroke has on walking function (Wade, Wood, Heller, Maggs, & Langton Hewer, 1987). When other parameters of walking are examined (e.g. gait velocity and spatiotemporal asymmetry) it becomes obvious that the majority of individuals with stroke are left with significant deficits in walking function even after rehabilitation (Patterson et al., 2008; Wade et al., 1987).

There are a number of characteristics in hemiparetic gait that are commonly seen and are measured by a variety of techniques including electromyography (EMG), kinematics and kinetics, tests of aerobic fitness, and finally spatiotemporal measures. EMG recordings during post-stroke gait have shown deviations in both the timing and amplitude of muscle activity (Knutsson & Richards, 1979; Peat et al., 1976). There are also changes in the magnitude and pattern of joint angles, power and moments associated with the lower limbs during walking post-stroke (Kim & Eng, 2004). Individuals with stroke also walk shorter distances with higher oxygen consumption compared to healthy adults (Cunha-Filho et al., 2003). Lastly, there are several deviations in spatiotemporal gait parameters after stroke. These include decreased cadence, decreased stride length, increased step width, increased double support and decreased gait velocity (Bohannon, 1987; Nakamura, Handa, Watanabe, & Morohashi, 1988; Goldie, Matyas, & Evans, 2001; Chen, Patten, Kothari, & Zajac, 2005). Furthermore, the unilateral nature of stroke leads to alterations in the spatial and temporal features of gait between the two limbs. These include a prolonged stance phase on the non-paretic side, a prolonged swing phase on the paretic side and an inequality in step length (Balasubramanian, Bowden, Neptune, & Kautz, 2007; K. K. Patterson et al., 2008). Not every individual with stroke will exhibit
all of these deviations. Instead each individual will present with a unique combination of deviations contributing to their gait dysfunction (Olney & Richards, 1996).

1.2.1 Gait Velocity after Stroke

Of all the spatiotemporal gait deviations after stroke, the hallmark deficit is a reduction of gait speed (von Schroeder, Coutts, Lyden, Billings, & Nickel, 1995). Normal, healthy gait speed is approximately 130 cm/s for females, and 140 cm/s for males (Bohannon, 1987), while in subacute stroke patients, velocity can be as low as 13 cm/s (Bale & Strand, 2008) and 53 cm/s on average in chronic stroke patients (Chen et al., 2005). Gait velocity reflects overall walking function and is associated with clinical performance-based measures of motor and sensory function, balance and overall function (Brandstater, de Bruin, Gowland, & Clark, 1983; Hsu et al., 2003; Langhammer, Lindmark, & Stanghell, 2006; Nadeau, Arsenault, Gravel, & Bourbonnais, 1999). Gait speed is an important factor to address clinically as it has been linked to independence and quality of life after stroke (Schmid et al., 2007).

1.2.2 Gait Asymmetry after Stroke

A stroke may also produce deficits resulting from hemiparesis that create left-right imbalances in the function or performance of the lower limbs. These asymmetries are important to study as they can provide insight into the control or quality of the walking pattern that a measure of gait velocity alone cannot (Patterson et al., 2008). Asymmetric gait can be either temporal or spatial in nature, or a combination of both.
Qualitatively, spatial asymmetry can be described as steps of uneven length between the paretic and non-paretic limb (Balasubramanian et al., 2007). There is variation within the stroke population in terms of which limb, the paretic or non-paretic limb, takes the longer step (Balasubramanian et al., 2007). This is different from temporal asymmetry, which is typically a prolonged swing phase and shortened stance phase on the paretic limb and vice versa on the non-paretic limb (Patterson et al., 2008). Asymmetry can be quantified with ratios of spatiotemporal gait parameters such as step length (spatial symmetry) and swing time (temporal symmetry). It has been reported that 55% of patients exhibit temporal asymmetry, and 33% of patients exhibit spatial asymmetries (Patterson et al., 2008). These asymmetries are important to address because they are linked to other negative consequences. For example, spatial asymmetry is related to poor forward propulsion and bone loss density in the paretic leg (Balasubramanian et al., 2007; Marzolini et al., 2014). Walking with temporal asymmetry may cause joint pain and degeneration in the unaffected leg due to repetitive and increased loading, inefficiency and compromised balance (Ellis, Howard, & Kram, 2013; Lewek, Bradley, Wutzke, & Zinder, 2014; Patterson et al., 2008). Furthermore, there is evidence that gait asymmetry does not improve with current rehabilitation practices and it may get worse over time (ie. into the chronic stages of stroke). (Patterson, Gage, Brooks, Black, & McIlroy, 2010a; Patterson et al., 2014; Turnbull & Wall, 1995).
1.2.3 Post-Stroke Deficits Related to Decreased Velocity and Asymmetry

To advance the rehabilitation of gait post-stroke, we must further understand underlying mechanisms that contribute to post-stroke walking deficits, such as slow gait velocity and spatiotemporal asymmetry. In identifying specific deficits, strategies and interventions can be designed to enhance and advance the current clinical practice. Due to the large number of possible factors that may contribute to asymmetric gait, there cannot be one overarching therapy that is applicable to every patient. Therefore, there must be more specific, targeted approaches tailored to the individual needs of the patient. To be able to utilize more targeted approaches, specific factors that affect gait will need to be identified for each individual patient. There are a number of stroke-related impairments known to play a role in gait. These include motor recovery, decreased strength, proprioception, spasticity and poor balance.

Motor recovery after stroke is related to gait function. Velocity is associated with various clinical measures of motor recovery including the Fugl-Meyer, the Motor Assessment Scale and the Chedoke-McMaster Stroke Assessment (Alexander et al., 2009; Brandstater et al., 1983; Nadeau et al., 1999). Individuals with poor recovery walk more slowly. Poor motor recovery is also related with greater spatial and temporal gait asymmetry (Alexander et al., 2009; Balasubramanian et al., 2007; Brandstater et al., 1983; Nadeau et al., 1999; Patterson et al., 2008). However, there is evidence that some individuals with good motor recovery still walk asymmetrically which suggests other factors besides motor recovery may play a role (Patterson et al., 2008).
Muscle weakness has also been shown to greatly affect gait. A number of lower limb muscles have been identified as important to gait velocity. Impaired muscle strength of the hip and knee greatly determined both the comfortable and fast gait velocities in a mild to moderately impaired stroke population (Hsu et al., 2003). Nadeau and coauthors (1999) also found hip flexor strength to be important in addition to plantarflexor strength. Lin and coauthors (2006) found that ankle dorsiflexor strength was the most important determinant of gait speed. Muscle strength has also been linked to spatiotemporal gait asymmetry. Hsu and colleagues (2003) showed that impaired ankle plantarflexor strength was significantly associated with single support time (or alternatively swing time) asymmetry.

Proprioception deficits have also been linked to gait impairments. Lin (2005) found that impaired joint position sense indirectly contributed to decreased velocity and step length. Lin (2005) proposed that individuals with stroke with impaired joint position sense may complain of “not knowing where their foot is” and thus may walk more slowly and take smaller steps in response to this. A later study by Lin and co-authors (2012) argue that although their study of proprioceptive interference from vibration did not find that impaired joint position sense affected gait, there may have been an increase in the use other available sensory modalities (i.e. vision and somatosensation) to compensate for the impaired proprioception in the control of gait.

Spasticity is a velocity-dependent increased resistance to passive stretch in a muscle that can occur after stroke (Bohannon, 1987). Spasticity is also related to gait deficits after stroke. Spasticity in the ankle plantarflexors is associated with both temporal and spatial asymmetry (Hsu et al., 2003; P. Lin et al., 2006). In addition, Lamontagne and
coauthors found that spasticity was negatively correlated with gait velocity and is believed to compromise the efficiency of ankle push-off (Lamontagne et al., 2001).

Finally, postural instability or decreased balance is also related to gait deficits after stroke. Gait velocity is correlated with Berg Balance Scale scores, which indicates a relationship between balance and the ability to walk faster after stroke (Langhammer et al., 2006; Patterson et al., 2007). In addition, instability in standing (indicated by increased posterior postural sway) is related to increased temporal gait asymmetry (Titianova & Tarkka, 1995).

In summary there are a number of known factors related to decreased velocity and spatiotemporal gait asymmetry after stroke. These include motor impairment, decreased muscle strength, impaired proprioception, spasticity and postural instability. However, these factors do not seem to explain all the variance in gait velocity and asymmetry observed in the stroke population. Further factors should be investigated so that more comprehensive interventions may be developed to provide improved walking outcomes for people with stroke.

1.3 Standing Balance after Stroke

It has been found that 80% of stroke patients have a balance disability, as measured by the Brunel Balance Assessment, in the acute phase after stroke (Tyson, Hanley, Chillala, Selley, & Tallis, 2006) and that 50% will continue to have some long-term disability in balance (Wolfe, 2000). The recovery of balance is important for
independent mobility as Michael (2005) reports that the severity of balance deficits predicts the ambulatory activity of stroke patients and is related to falls in the community. Impaired balance control has also been found to be associated with a risk of falls in stroke patients (Lamb et al., 2003; Teasell, McRae, Foley, & Bhardwaj, 2002). A study found that 73% of patients report a fall in the community within 6 months of discharge (Forster & Young, 1995) and that 50% have a fall within one year (Hyndman, Ashburn, & Stack, 2002). It was reported that falls in a community-ambulating stroke population were associated with balance deficits while walking (Belgen, Beninato, Sullivan, & Narielwalla, 2006).

Similar to hemiparetic gait, there are hallmark deficits related to standing balance. These are typically measured with force plates (either both feet on one plate or each foot on a separate plate) and various parameters are reported such as vertical ground reaction force, the percentage of body weight borne on each leg and centre of pressure (COP) velocity and displacement. COP values can be reported as a total of all directions or separated out into the anteroposterior and mediolateral directions. Winter and coauthors (1996) report that displacements in these directions reflect stabilizing flexion-extension ankle torque and lateral weight shift respectively. These torques and weight shifting are applied to the supporting surface to maintain the body’s centre of mass within the base of support (i.e. the feet) so that stability in standing is achieved (Marigold & Eng, 2006).

One hallmark of standing balance in stroke patients is altered weight distribution patterns compared to healthy individuals (Goldie et al., 2001). The hemiparesis will cause the patients to favour one limb for the control of balance, most often the non-paretic limb (Geurts, de Haart, van Nes, & Duysens, 2005). This may in turn impair the
use of the affected limb’s muscles for coordinated balance reactions, thus creating an increased risk of a fall (de Haart, Geurts, Huijdekoper, Fasotti, & van Limbeek, 2004). There will be altered centre of pressure (COP) trajectories under the paretic limb (Genthon et al., 2008) and these trajectories may reflect less use of the paretic limb for the control of balance.

Another hallmark is increased COP displacement which Geurts and coauthors note indicates increased body sway as well as exaggerated balance adjustments made by the ankle (Geurts et al., 2005). Marigold and coauthors (2006) reported mean RMS COP displacement values of 0.36 (0.093) cm and 0.178 (0.052) cm in the AP and ML direction respectively. These were significantly greater than a group of age-matched controls, which exhibited a mean AP RMS COP value of 0.197 (0.061) cm and ML COP value of 0.093 (0.028) cm. The instability after stroke gradually decreases during rehabilitation but the COP displacement and weight-bearing values may not reach normal values for healthy older adults (Geurts et al., 2005).

One alternative way to report COP displacement is to calculate an index of displacement using paretic and non-paretic limb values (Hendrickson, Patterson, Inness, McIlroy, & Mansfield, 2014). This value can reflect the fact that the limbs do not contribute equally to standing balance after stroke (Genthon et al., 2008). This index can range from 0 to 1 and a value of 0.5 indicates the limbs are making equal contribution to standing balance. A value greater than 0.5 indicates the non-paretic limb is making a larger contribution to standing balance control. Hendrickson and coauthors (2014) reported a mean index value of 0.57 (0.12) for individuals admitted to inpatient stroke rehabilitation.
1.3.1 Post-Stroke Deficits Related to Decreased Standing Balance

There are a number of known factors that contribute to impaired standing balance after stroke and these are similar to those known to affect gait. These include impaired proprioception, asymmetric weight bearing and decreased strength.

Proprioception has been shown to affect postural stability. One study found those with intact ankle proprioception had far less postural sway compared to those with impaired ankle position sense (Niam et al., 1999). This agrees with previous research that highlighted the importance of proprioception to balance control (Keenan, Perry, & Jordan, 1984). Marigold (2004) also cites the large importance of proprioception for controlling balance.

As mentioned previously, there exists a loading or weight bearing asymmetry in standing after stroke. A reduction in loading of the paretic leg will impair the use of the affected limb’s muscle for coordinated reactions to shifts in posture (Mansfield et al., 2013). It has been shown that those with a greater standing asymmetry (outside of the range 47-53% of weight borne through one limb) have increased postural sway in the medio-lateral (ML) direction (Mansfield et al., 2013; Marigold & Eng, 2006). The authors suggest that the greater mass stacked over one limb led to the greater sway due to the mechanically unstable posture.

Finally, muscle strength also affects standing balance. Muscle weakness is one of the most strongly associated factors to standing balance (Tyson et al., 2006). Marigold
(2004) found that muscle strength greatly contributed to postural instability in the most challenging conditions of a Sensory Organization Test (SOT).

1.4 Somatosensation after stroke

Sixty percent of individuals with stroke have been reported to present with some form of somatosensory deficit (Winward, Halligan, & Wade, 1999). Somatosensation includes proprioception (i.e. joint position sense and kinesthesia) and cutaneous sensation (i.e. light touch and vibration). Both proprioception and cutaneous sensation can be altered after stroke but deficits in cutaneous sensation are more frequently observed (Tyson, Hanley, Chillala, Selley, & Tallis, 2008). Furthermore, the leg appears to be affected more frequently than the arm. Cutaneous sensation and more specifically cutaneous sensation at the plantar aspect of the foot is the focus of this thesis.

Sensory stimulation to the skin is detected by peripheral sensory receptors (i.e. Merkel cells and Ruffini endings) located in the skin and this afferent information is transmitted to the brain by the dorsal column-medial lemniscus pathway (DCML) (Kandel, 2013; Perry, McIlroy, & Maki, 2000; Zhang & Li, 2013). The DCML pathway is a three-neuron pathway (Kandel, 2013). The first order neuron comprises the primary sensory afferent with the receptor in the periphery and an axon which enters the spinal cord and ascends in the dorsal column (Kandel, 2013). This first order neuron synapses in the medulla (Kandel, 2013). The second order neuron leaves the medulla, crosses the midline to form the medial lemniscus and synapses in the thalamus (Kandel, 2013). The third order neuron leaves the thalamus and eventually terminates in the primary somatosensory cortex located on the post-central gyrus (Kandel, 2013).
The sensory loss observed after stroke may be due to damage to any central part of the pathway but is mainly caused by damage to the primary somatosensory (SI) cortex (Carey, 1995). Damage to the SI can result in the inability to accurately perceive, process and interpret sensory feedback. If the CNS is unable to accurately integrate the sensory information generated by movement, it may result in an abnormal motor response and altered movement patterns, which will, in turn, contribute further altered sensory feedback and create a vicious cycle of gait and balance deficits (Wutzke, Mercer, & Lewek, 2013).

Recovery from somatosensory deficits likely depends on the capacity for neural recovery and cortical reorganization (Carey, 1995). Most patients exhibit recovery in the first 3 months after stroke (Newman, 1972). However, a common limitation of studies of sensory impairments after stroke is the use of gross measures of sensation that do not accurately reflect the complex nature of cutaneous sensation. For example, the Rivermead Assessment of Somatosensory Performance (RASP) is a clinical measure designed to provide a brief, quantifiable assessment of somatosensory function in individuals with neurological conditions (Winward, Halligan, & Wade, 2002). The RASP includes seven tests of sensation that cover a range of modalities including light touch, sharp/dull, temperature and proprioception (Winward et al., 2002). While this measure is valid and reliable for use in the stroke population (Winward et al., 2002) it may be limited in sensitivity and discrimination for research studies that aim to investigate the specific contribution of one form of sensation to complex motor skills such as gait and balance. This is because the RASP ultimately summates the performance on each of the sensory tests into a score on an ordinal scale.
1.5 Role of plantar cutaneous sensation in gait and balance

Many studies have identified that sensation may be a factor related to standing balance and ambulation (Hendrickson et al., 2014; Marigold et al., 2004; Tyson et al., 2006). As described above, the role for proprioception in gait and balance after stroke has been investigated. The role of cutaneous sensation in post-stroke balance and gait has received less attention.

The physiology of cutaneous sensation of the plantar aspect of the foot supports its role in gait and balance. The plantar surface of the foot has been described as a “sensory map” that provides the central nervous system information about the position of the body based on the distribution of activated receptors (Alfuth & Rosenbaum, 2012; Kavounoudias, Roll, & Roll, 1998). Plantar skin receptors are sensitive to pressure and vibration and can be activated with a common clinical assessment tool – monofilaments (Alfuth & Rosenbaum, 2012). Kennedy and Inglis (2002) mapped cutaneous receptors in the foot sole using monofilaments and recording from the tibial nerve and found that (unlike similar receptors in other areas of the body) there is no background activity in the receptors when the foot is in an unloaded position. This combined with the fact that there were relatively fewer receptor units in the longitudinal arch of the foot compared to the heel and metatarsal heads suggests that plantar receptors have an important role for signaling pressure distribution when the foot is in contact with a supporting surface (Kennedy & Inglis, 2002). While cutaneous receptors appear to be distributed throughout the foot sole, there is conflicting evidence about the sensitivity of receptors at various
regions of the foot. Kennedy and Inglis (2002) found no significant difference in activation thresholds between the toes, lateral foot and heel while Jeng and coauthors (2000) reported the lesser toes and arch to be the most sensitive to monofilament testing and the heel to be the least sensitive. This difference in results might be due to the difference in testing methods; Kennedy and Inglis (2002) used recordings from the tibial nerve to determine receptor activation while Jeng and coauthors relied on subjective report of perception by the study participants (Jeng et al., 2000). Regardless of variations in sensory threshold, the cutaneous receptors in the foot appear to be designed to provide information about pressure distribution and loading when the foot is in contact with the floor which can be used to regulate postural control during standing and gait.

The role of plantar cutaneous sensation during gait and balance is typically investigated using two different approaches; 1) comparing gait and balance performance in individuals with known sensory loss (e.g. individuals with diabetes) to individuals with intact sensation or 2) inducing an artificial sensory loss in healthy individuals using an anesthetic or an ice immersion bath and examine the resulting effects on gait and balance.

Peripheral nerve damage occurs in about 25% of individuals who have had diabetes for 10 years (Menz, Lord, St George, & Fitzpatrick, 2004). This damage is associated with sensory loss including light touch, vibration sense and proprioception (Menz et al., 2004). It is believed that this sensory loss has an impact on both gait and balance in the diabetic population. For example, there is evidence that increasing levels of cutaneous sensory loss is associated with postural instability as measured by increased postural sway and increased COP velocity (Kanade, Van Deursen, Harding, & Price, 2008; Meyer, Oddsson, & De Luca, 2004; Wang & Lin, 2008). Furthermore, individuals
with diabetes and sensory loss due to peripheral neuropathy show gait deviations. For example, when compared to healthy, age-matched controls, individuals with diabetic peripheral neuropathy have reduced gait velocity, cadence and step length (Menz et al., 2004). Individuals with diabetic peripheral neuropathy spend a shorter time in single limb stance and have increased reaction times when walking while performing a secondary cognitive task (Courtemanche et al., 1996).

The second line of evidence for the role of plantar sensation in gait and balance comes from studies of healthy adults where sensory loss is artificially induced. Artificial sensory loss can be created in healthy adults using a variety of techniques including local anaesthesia, ischemia and inducing hypothermia (Taylor, Menz, & Keenan, 2004). When such sensory loss is induced, healthy adults exhibit altered pressure patterns and increased COP velocity in standing (Meyer et al., 2004; Zhang & Li, 2013). Experimental sensory loss also has an effect on gait. For example, healthy adults will demonstrate altered pressure patterns under the feet and kinetic and kinematic changes at the knee and ankle (e.g. higher knee extensor moments) (Eils et al., 2002; Hohne, Ali, Stark, & Bruggemann, 2012).

In summary, support for a role of plantar sensation in gait and balance can be derived from studies in the diabetic population as well as studies that artificially induced sensory loss in healthy individuals. However, the direct application of these results to the role of plantar sensation in gait and balance after stroke is limited. First, from these studies it is often difficult to separate the specific contribution of plantar sensation to gait and balance from that of proprioception since often both of these sensory modalities are impaired by peripheral neuropathy and some methods of inducing artificial sensory loss.
Second with respect to the diabetic studies, there is a difference in the nature of plantar sensation loss. In the diabetic population the loss is peripheral in nature where as in the stroke population the sensory loss is of a central origin. Therefore information about how plantar sensation loss affects balance and gait after stroke is needed.

1.6 Vision as compensation for sensory loss

In addition to sensation, vision and vestibular input are utilized in the control of standing balance. The information from these sources at times is redundant and at other times may be conflicting (Bonan et al., 2004). Therefore, the central nervous system needs to evaluate each form of sensory information, integrate it, and select the input to attend to (Bonan et al., 2004). It has been proposed than when sensory information is lost, individuals with stroke compensate with greater utilization of visual input to maintain postural control during standing (Marigold & Eng, 2006). One common method to determine the level of compensation by vision is to use the Romberg Quotient, a ratio of postural variables in eyes closed vs. eyes open conditions during standing (Le & Kapoula, 2008). Marigold (2006) studied standing balance in individuals with stroke and found that postural sway increased when participants closed their eyes. However, this study did not include a measure of sensation. Therefore, it is currently unknown whether cutaneous sensory loss after stroke is related to the use of vision as a compensatory strategy in the control of standing balance.
1.7 Research Questions and Objectives

It is not yet clear how cutaneous sensation in the paretic foot is related to gait and standing balance function post-stroke. Thus, there is a need to study these associations using detailed assessment of cutaneous plantar sensation and quantitative measures of standing balance and gait after stroke. Advancing our understanding of the underlying deficits related to balance and gait dysfunction post-stroke could help identify new intervention targets and strategies. Furthermore, it is important to understand compensatory strategies (such as reliance on visual input) that individuals with plantar sensation loss after stroke may use to maintain upright standing. If there are significant associations between plantar sensation loss, gait and balance dysfunction and reliance on vision as a compensatory strategy then this information could guide the development of interventions specifically to aid in the recovery of sensory-related impairments and reduction of compensatory strategies with the goal of improving gait and balance function post-stroke.

The main objectives of this thesis are to investigate the relationship between plantar sensation and 1) standing balance control, 2) gait post-stroke and 3) an over-reliance on visual input as a compensatory strategy during the control of standing balance.

This thesis hypothesizes that those with impaired plantar sensation (defined as having a score above a normative cutoff for monofilament testing) will:
1) have decreased stability compared to those with intact sensation as measured by the root mean square (RMS) of COP displacement in the anteroposterior and mediolateral directions,

2) show more impaired gait as measured by velocity and step length and swing time symmetry ratios,

3) load their non-paretic limb to greater extent when vision is occluded, and exhibit increased reliance on vision the Romberg Quotient for standing balance.
Chapter 2

2 Methods

This study is a secondary analysis of data collected at the Balance, Mobility, and Falls Clinic (BMFC) at Toronto Rehab- University Health Network (Toronto, ON).

The BMFC is a novel on-site clinic that integrates clinical measures of gait and balance with laboratory measurement and technology. The standardized assessment performed is considered routine care at this location (Inness et al., 2010). The assessments are performed by a physiotherapist at admission to the inpatient stroke unit and again at discharge. The measures taken are entered into each patient’s care record and into a database managed by the Mobility Team of the Research Department at Toronto Rehab. The data for this project was extracted from this database for the secondary analysis.

2.1 BMFC Testing Protocol

Though details of the BMFC assessment have been described elsewhere (Mansfield, Mochizuki, Inness, & McIlroy, 2012), the components of the testing protocol relevant to the present study will be described in detail here.
2.1.1 Clinical Measures

**Berg Balance Scale:**

The Berg Balance Scale (BBS) is a performance-based measure of balance consisting of movements deemed important by patients and health professionals (Berg, 1989). The items are designed to determine a patient’s ability to maintain balance while performing tasks. Each task in the 14-item test is scored on a 5-point ordinal scale with 0 representing an inability to complete the task and 4 representing the ability to complete the task safely with no assistance. The maximum possible score on the BBS is 56, and an individual with a score of less than 45 is considered to have balance impairment (Zwick, Rochelle, Choksi, & Domowicz, 2000).

In stroke, this test is best used in a population that is not as advanced in recovery, as the tasks may not be suited or challenging enough to a more advanced or mobile group who might obtain a maximum score but still have some disability (Berg, 1989). In addition, this test is not suitable for severely affected individuals, as there only exists one item — sitting — that may be tolerated by this group (Mao, Hsueh, Tang, Sheu, & Hsieh, 2002). In a stroke population, this scale has been shown to have both high intra-rater reliability (ICC= 0.97) and inter-rater reliability (ICC=0.98) in therapists who received no prior training before administering the test and an independent evaluator (Berg, Wood-Dauphinee, & Williams, 1995). Though it has been shown to have a ceiling effect (Salbach et al., 2001), Wee and co-authors suggest the Berg Balance Scale is particularly suited for an acute population (mean and standard deviation (SD) days post stroke 28.7
(26.5)), as patients do not achieve the maximum score at this stage of recovery (Wee, Bagg, & Palepu, 1999).

**Chedoke McMaster Stroke Assessment:**

The Chedoke McMaster Stroke Assessment (CMSA) is a two part measure consisting of a physical impairment inventory, which classifies stroke patients based on their stage of motor recovery, and a disability inventory which measures changes in disability or physical function (Gowland et al., 1993). Its purpose is to determine the presence and severity of physical impairments in order to classify patients, assist with planning interventions and evaluate intervention effectiveness (Gowland et al., 1993). This analysis used the CMSA impairment inventory scores for the leg (CMSA$_{leg}$) and foot (CMSA$_{foot}$) as measures of motor recovery. Both inventories are scored on a scale of 1-7 with 1=flaccid paralysis, 3=spasticity found but voluntary movement present, 5=spasticity markedly reduced but still present with rapid movement, and 7= normal movement (Gowland et al., 1993).

This test does require training for the tester before administration, and has been deemed as having excellent reliability for both the leg (intrarater ICC=0.98, interrater ICC=0.85) and foot scales (intrarater ICC=0.94, interrater ICC=0.91) (Gowland et al., 1993). The CMSA also has high construct validity shown through excellent correlation with the Fugl-Meyer test, a performance-based impairment index (r=0.95, p=<0.001) (Gowland et al., 1993; Poole & Whitney, 2001).
**Plantar Sensation:**

The Semmes-Weinstein monofilaments were used to measure the plantar sensation of the foot on the paretic side (North Coast Medical Inc., Morgan Hill, CA). The testing procedure consists of applying pressure to the base of the heel along the midline of the affected foot and at the 5th metatarsal head using monofilaments of decreasing thickness. Each of the 20 monofilaments has a corresponding value that indicates the amount of force required to bend the wire against the skin. Individuals were asked to state whether they felt the presence of the monofilament’s pressure application. If the individual stated they were aware of the presence of the monofilament on their skin, they were considered to have intact sensation at the corresponding force level. The values presented for each monofilament represent marker values produced by the equation: marker value = $\log_{10} [\text{force (in mg)} \times 10]$ (Mueller, 1996). Scores for this test range from 1.65 to 6.65 (Mueller, 1996). Lower scores represent intact sensation and higher scores representing reduced cutaneous sensation.

Though this test has not been studied specifically for the lower limb in a stroke population, it has been shown to be a reliable test for sensation in a diabetic population when testing for “loss of protective sensation.” Protective sensation is threshold of sensitivity to pressure at the plantar aspect of the foot necessary to avoid the development of plantar ulcers (Mueller, 1996). Studies show the test is reproducible and suitable for everyday clinical testing (Bell-Krotoski, Fess, Figarola, & Hiltz, 1995; Valk et al., 1997).
2.1.2 Laboratory Measures

Standing balance:

Standing balance was assessed using 2 force plates (Advanced Medical Technology Inc., Watertown, MA, USA) placed side by side with less than 1 mm of separation between. Ground reaction forces under each foot were sampled at 256 Hz and low pass filtered using a 4\textsuperscript{th} order dual-pass Butterworth filter at 10Hz. Patients stood with one foot on each force plate in a standardized foot position: stance width of 0.17m between the mid-heels and a foot angle of 14 degrees to the mid-sagittal plane along the line between the mid-heel and the centre of the great toe (McIlroy & Maki, 1997). This position is used to account for the large variations in individual’s preferred placement of foot position, and most accurately depicts natural standing behavior (McIlroy & Maki, 1997).

Quiet standing balance was measured under the following 3 conditions: eyes open, eyes closed, and maximal loading of the paretic limb with eyes open. The eyes open and eyes closed conditions were recorded for 30 seconds. Under the maximal loading condition, patients were asked to shift their weight to their affected limb and bear as much weight as possible through that limb. This trial was collected over 20 seconds due to the individual’s decreased tolerance to maximally load their paretic limb for the full 30 seconds that the first trials were collected under. While the eyes open and eyes closed standing conditions reflect the individual’s ability to spontaneously bear weight with and without visual input, the maximal load condition is a reflection of the individual’s maximal weight bearing capacity of their affected limb (Hendrickson et al., 2014).
Over-ground Gait Assessment:

Spatiotemporal gait measures were recorded using a pressure sensitive mat (GAITrite system, CIR Systems Inc., Clifton, NJ, USA). The mat is 4.6 m long and 0.9 m wide and has a grid of 48x288 pressure sensitive sensors (13824 total) that are activated by each footfall event as the individual walks across the mat. Individuals walked the length of the mat at their preferred pace, beginning 1 m from the edge of the mat and continued 1 m past the end. This allowed for acceleration and deceleration to be completed while off of the mat and ensured that each footfall collected was that of consistent, steady state walking. A minimum of 18 footfalls were collected for each individual to ensure reliability of the data. Spatiotemporal gait parameters were automatically calculated by the custom GAITrite software based on timing and location of sensor activation caused by footfall events. Compared to a Clinical Stride Analyzer – a system of footswitches inside the shoe with a waist-worn data logger that has already shown high reliability and validity in various movement disorders (Bilney, Morris, & Webster, 2003) – GAITrite showed high level of agreement for gait speed (ICC=0.99), cadence (ICC=0.99), and stride length (ICC=0.99) during preferred pace, slow and fast pace trials (Bilney et al., 2003). The same study also found good reliability between trials for gait speed, cadence, stride length, single leg support time, and double limb support (ICC range 0.84-0.97).
2.2 Data Extraction

Data was extracted from the BMFC database on January 27, 2014. Data from individuals with stroke collected between October 2009 and October 2011 were included in the analysis if they met the following inclusion criteria: 1) able to stand independently for 30 seconds without a mobility aid; 2) able to walk 10 metres independently without an aid or physical assistance from another individual; 3) able to follow verbal instructions; and 4) having complete scores of plantar sensation in the affected limb at the admission testing point.

Individuals were excluded if they met the following criteria: 1) previous lower limb orthopedic surgeries, prosthetics or ankle-foot orthotics; 2) history of other neurological conditions that would influence gait (e.g. Parkinson’s, Cerebellar Ataxia); 3) bilateral stroke and/or bilateral stroke-related sensorimotor impairment; 4) presence of diabetes. A total of 92 individuals met the required criteria and were included in the secondary analysis.

Measures of demographics including age, length of stay (LOS), days post stroke (DPOST) were extracted from the database, as well as measures of functional status included the level of motor impairment in the leg and foot from the Chedoke McMaster assessment (CMSA_{foot}, CMSA_{leg}) and the Berg Balance Scale (BBS).
2.3 Calculations and Measurements

The following measures of interest were extracted and in some cases further calculations were performed with the data extracted from the BMFC database.

2.3.1 Standing Balance:

1) Weight bearing on the paretic limb

Measures of loading were calculated from the mean vertical force generated by the limb and was expressed as a percentage of body weight in the eyes open (\(\%\text{BW}_{\text{quiet}}\)), eyes closed (\(\%\text{BW}_{\text{quietEC}}\)) and maximum loading condition (\(\%\text{BW}_{\text{load}}\)).

2) RMS of Centre of Pressure displacement

Calculated separately for each force plate was the centre of pressure (COP) displacement in both the medio-lateral (ML) and antero-posterior (AP) directions. Postural sway was quantified as the root mean square (RMS) of antero-posterior (RMS\(_{\text{AP}}\)) and medio-lateral (RMS\(_{\text{ML}}\)) COP displacement calculated separately for each force plate as well for the total displacement for the force plates combined (RMS\(_{\text{APtot}}\) and RMS\(_{\text{MLtot}}\)). RMS values were also calculated in the maximal loading condition for both directions (RMS\(_{\text{APload}}\), RMS\(_{\text{MLload}}\)).

3) Index of RMS AP-COP displacement
An index was calculated using values for the RMS of the COP displacement (Symmetry Index, SI) in the AP direction under the paretic and non-paretic limbs (Eq 1).

Equation 1. \[ SI = \frac{Non-\text{paretic limb value}}{(Paretic \text{ limb value} + Non-\text{paretic limb value})} \]

This ratio indicates which limb is contributing more heavily to the control of standing balance (Hendrickson et al., 2014). The index can range from a score of 0 to 1, with 0.5 indicating equal contributions of the paretic and non-paretic limbs to standing balance. If the index is greater than 0.5, it means the RMS for the non-paretic limb is higher compared to the paretic limb, and is being utilized more for balance control (Hendrickson et al., 2014).

4) Romberg Quotient

The Romberg quotient (RQ) is typically calculated as a ratio of postural sway measures in the eyes closed vs. eyes open conditions (Eq. 2) (Le & Kapoula, 2008).

Equation 2. \[ RQ = \frac{\text{Eyes closed value}}{\text{Eyes open value}} \]

In the present study, the RMS of AP and ML COP displacement in the eyes closed and eyes open condition were used for this calculation (RQ_{AP} and RQ_{ML}, respectively). The Romberg quotient reflects the influence of vision on postural stability (Black, Wall III, Rockette Jr, & Kitch, 1982). The COP displacement recorded when an individual’s eyes are closed, is thought to reflect the ability to control posture without visual input, relying on vestibular and somatosensory input instead. Therefore, increased
COP displacement in the eyes closed condition reflects greater instability when visual input is removed. It is hypothesized that the increase in displacement in the eyes closed compared to the eyes open condition reveals a strategy of increased reliance on vision for the control of posture. A quotient $> 1.0$ indicates a greater COP displacement in the eyes closed condition and greater values of the RQ indicate a greater need for vision to maintain balance.

2.3.2 Over-ground gait:

1) Velocity

Velocity is the speed of the individual as they walked across the GAITrite system, expressed in cm/sec. It is calculated automatically by the GAITrite software. This measure is generally used as a gauge of overall gait performance to track rehabilitation and functional ability (Dickstein, 2008). Gait speed is responsive and able to detect change in function (Salbach et al., 2001), and has been shown to be a reliable measure of walking ability in an inpatient stroke population undergoing rehabilitation (ICC=0.86) (Fulk & Echternach, 2008).

2) Step and Swing Symmetry

Gait symmetry ratios were calculated using values of step length (cm) ($R_{\text{step}}$) (Eq 3) and swing time (sec) ($R_{\text{swing}}$) (Eq 4) from the paretic and non-paretic limbs.

\[
\text{Equation 3} \quad R_{\text{step}} = \frac{\text{Larger Step Length value}}{\text{Smaller Step length value}}
\]
Equation 4

\[ R_{\text{swing}} = \frac{\text{Larger swing time value}}{\text{Smaller swing time value}} \]

Measuring gait symmetry can provide insight into the control of walking and is used to assess differences between the lower limbs that may alter gait (Patterson et al., 2010a). This ratio equation has been tested alongside a number of other variations of symmetry equations outlined by Patterson and colleagues (Patterson, Gage, Brooks, Black, & McIlroy, 2010b), which were highly correlated with each other. Though each equation was not significantly different from the others, this ratio equation was recommended for its ease of use and interpretation. Lewek (2011) reports high ICC for the symmetry equations for step length asymmetry (0.976) and swing time symmetry (0.962).

2.3.3 Classification by Plantar Sensation

Individuals were sorted into normal and impaired sensation groups based on the monofilament scores from sensation testing at two locations on the foot of the paretic side: the heel of the foot (HEEL) and the base of the 5th metatarsal phalangeal joint (5MTP). Each individual’s score was compared to age-based threshold cutoffs (Plucknette, Terryberry, Brogan, & Anain, 2012) monofilament test scores for protective sensation. Patients who were between 35 and 64 years old, and who were above a cutoff monofilament score of 4.31 were classified as having impaired plantar sensation. Patients who were over the age of 65 and above a cutoff monofilament score of 4.74 were also classified as having impaired sensation (HEEL impaired, 5MTP impaired). Those
individuals that had monofilament scores below these cutoffs were considered to have plantar sensation within normal limits (HEEL\textsubscript{intact}, 5MTP\textsubscript{intact}).

2.3.4 Statistical Analysis

All calculations and statistical analyses were performed using SAS 9.3 (SAS Institute Inc., Cary, NC, USA).

Group means and standard deviations (SD) were calculated for the entire study group and the impaired and intact sensation groups. The statistical analyses comparing group means were performed separately for each monofilament testing site; HEEL\textsubscript{intact} compared against HEEL\textsubscript{impaired} and 5MTP\textsubscript{intact} compared against 5MTP\textsubscript{impaired}. Using a t-test, the groups were compared for age, LOS, DPOST, BBS, CMSA\textsubscript{foot} and CMSA\textsubscript{leg} to determine if any group differences existed. Spearman correlations were performed between monofilament test scores at the HEEL and 5MTP, and measures of loading (%BW\textsubscript{quiet}, %BW\textsubscript{quietEC}, %BW\textsubscript{load}), balance (RMS\textsubscript{APtot}, RMS\textsubscript{MLtot}, RMS\textsubscript{APload}, RMS\textsubscript{MLload}, RQ\textsubscript{AP}, RQ\textsubscript{ML}, and SI) and gait (R\textsubscript{swing}, R\textsubscript{step}, and Velocity). Because the exploratory nature of the study, and the large number of variables used in the analysis, the Holm method was utilized to account for multiple comparisons (Hochberg & Benjamini, 1990; Holm, 1979). The statistical methods for each research objective are outlined below:
2.3.4.1 Research Objective 1: Plantar sensation and standing balance control

To determine the extent to which sensation plays a role in standing balance, the HEEL$_{impaired}$ and HEEL$_{intact}$ and 5MTP$_{impaired}$ and 5MTP$_{intact}$ groups were compared. ANCOVAs were performed with CMSA$_{foot}$ as a covariate, on the following variables: BBS, SI, RMS$_{APtot}$, RMS$_{MLtot}$, RMS$_{APload}$, RMS$_{MLload}$, %BW$_{quiet}$, and %BW$_{load}$. The Holm method was used to account for multiple comparisons. The initial adjusted level of significance was 0.00625 (8 comparisons).

2.3.4.2 Research Objective 2: Plantar sensation and gait

To investigate the role of sensation in gait the HEEL$_{impaired}$ and HEEL$_{intact}$, and 5MTP$_{impaired}$ and 5MTP$_{intact}$ groups were compared. ANCOVAs were performed with CMSA$_{foot}$ as a covariate on 3 gait variables: velocity, R$_{swing}$ and R$_{step}$. The Holm method was used to account for multiple comparisons. The initial adjusted level of significance was 0.0167 (3 comparisons).

2.3.4.3 Research Objective 3: Plantar sensation, vision and control of posture

To investigate the extent to which individuals with stroke rely on vision to control upright posture, ANCOVAs were performed with CMSA$_{foot}$ scores as a covariate on the
following variables: $\%{BW}_{quietEC}$, $RQ_{AP}$ and $RQ_{ML}$. Comparisons were made between the HEEL impaired and HEEL intact groups and the 5MTP impaired and 5MTP intact groups. The Holm method was used to account for multiple comparisons. The initial adjusted level of significance was 0.0167 (3 comparisons).
Chapter 3

3 Results

3.1 Participants

A total of 92 individuals were included in the analysis. The mean and standard deviation (SD) for each variable for the entire study group are included in Table 1. The number of participants (N) has been included in each table as the numbers varied for each variable. This is due to the fact that some patients were not able to complete the testing at the time of assessment, as they may not have had the appropriate level of function (i.e., they were not ambulatory).

Table 1: Averages for Study Population

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE</td>
<td>92</td>
<td>67.9</td>
<td>13.2</td>
<td>65.2-70.6</td>
</tr>
<tr>
<td>LOS</td>
<td>92</td>
<td>37.5</td>
<td>24.0</td>
<td>32.6-42.4</td>
</tr>
<tr>
<td>DPOST</td>
<td>92</td>
<td>16.6</td>
<td>14.8</td>
<td>13.58-19.62</td>
</tr>
<tr>
<td>BBS</td>
<td>92</td>
<td>32.4</td>
<td>18.8</td>
<td>28.56-36.24</td>
</tr>
<tr>
<td>CMSAfoot</td>
<td>85</td>
<td>3.98</td>
<td>1.44</td>
<td>3.67-4.29</td>
</tr>
<tr>
<td>CMSAleg</td>
<td>85</td>
<td>4.42</td>
<td>1.28</td>
<td>4.15-4.69</td>
</tr>
<tr>
<td>HEEL</td>
<td>92</td>
<td>4.57</td>
<td>0.66</td>
<td>4.44-4.7</td>
</tr>
<tr>
<td>5MTP</td>
<td>90</td>
<td>4.36</td>
<td>0.6</td>
<td>4.24-4.48</td>
</tr>
<tr>
<td>%BWquiet</td>
<td>86</td>
<td>47.27</td>
<td>8.83</td>
<td>45.40-49.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>%BW_{quietEC}</td>
<td>86</td>
<td>47.56</td>
<td>8.92</td>
<td>45.67-49.44</td>
</tr>
<tr>
<td>%BW_{load}</td>
<td>85</td>
<td>74.18</td>
<td>13.62</td>
<td>71.29-77.08</td>
</tr>
<tr>
<td>RMS_{AP\text{tot}}</td>
<td>86</td>
<td>6.55</td>
<td>2.85</td>
<td>5.94-7.15</td>
</tr>
<tr>
<td>RMS_{ML\text{tot}}</td>
<td>86</td>
<td>4.44</td>
<td>2.87</td>
<td>3.83-5.05</td>
</tr>
<tr>
<td>RMS_{AP\text{load}}</td>
<td>85</td>
<td>8.24</td>
<td>3.39</td>
<td>7.52-8.96</td>
</tr>
<tr>
<td>RMS_{ML\text{load}}</td>
<td>85</td>
<td>8.29</td>
<td>4.80</td>
<td>7.27-9.31</td>
</tr>
<tr>
<td>RQ_{AP}</td>
<td>86</td>
<td>1.35</td>
<td>0.42</td>
<td>1.26-1.44</td>
</tr>
<tr>
<td>RQ_{ML}</td>
<td>86</td>
<td>1.38</td>
<td>0.76</td>
<td>1.22-1.54</td>
</tr>
<tr>
<td>SI</td>
<td>86</td>
<td>0.56</td>
<td>0.12</td>
<td>0.54-0.59</td>
</tr>
<tr>
<td>R_{swing}</td>
<td>65</td>
<td>1.16</td>
<td>0.27</td>
<td>1.09-1.23</td>
</tr>
<tr>
<td>R_{step}</td>
<td>65</td>
<td>1.09</td>
<td>0.11</td>
<td>1.06-1.12</td>
</tr>
<tr>
<td>Velocity (cm/s)</td>
<td>65</td>
<td>67.8</td>
<td>32.5</td>
<td>59.9-75.7</td>
</tr>
</tbody>
</table>

Means for all demographic and clinical variables included in the analysis. Included are the number of participants (N), standard deviation (SD) and the 95% confidence interval (CI) for each variable.

The total group was separated into impaired and intact groups for both of the HEEL and 5MTP sensory testing locations based on age-matched normative values (Plucknette et al., 2012). There were 51 and 41 individuals in the HEEL_{intact} and HEEL_{impaired} groups, and there were 64 and 28 individuals in the 5MTP_{intact} and 5MTP_{impaired} groups respectively. The HEEL_{intact} had a larger CMSA_{foot} score compared to HEEL_{impaired} (p= 0.038). The HEEL_{intact} and HEEL_{impaired} groups did not differ on any other demographic variable. No differences were present between 5MTP_{intact} and
5MTP\textsubscript{impaired} sensation groups on any demographic or motor impairment variable. The means for each group are presented in Tables 2 and 3.

Table 2: Group Averages for Demographics and Clinical variables for HEEL

<table>
<thead>
<tr>
<th></th>
<th>HEEL\textsubscript{intact} (n=51)</th>
<th>HEEL\textsubscript{impaired} (n=41)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>95% CI</td>
</tr>
<tr>
<td>AGE</td>
<td>51</td>
<td>67.1 (13.7)</td>
<td>63.34-70.86</td>
</tr>
<tr>
<td>LOS</td>
<td>51</td>
<td>33.5 (16.7)</td>
<td>28.92-38.08</td>
</tr>
<tr>
<td>DPOST</td>
<td>51</td>
<td>16.4 (11.9)</td>
<td>13.13-19.67</td>
</tr>
<tr>
<td>CMSA\textsubscript{foot}</td>
<td>49</td>
<td>4.27 (1.39)</td>
<td>3.88-4.66</td>
</tr>
<tr>
<td>CMSA\textsubscript{leg}</td>
<td>49</td>
<td>4.6 (1.22)</td>
<td>4.26-4.94</td>
</tr>
</tbody>
</table>

Mean, standard deviation (SD) and 95% confidence intervals for demographic and clinical variables for HEEL\textsubscript{impaired} and HEEL\textsubscript{intact} group. The patient population was separated into intact (HEEL\textsubscript{intact}) and impaired (HEEL\textsubscript{impaired}) based on normative cutoffs. T-test was performed to identify group differences. (***) indicate statistical significance.

Table 3: Group Averages of Demographic and Clinical Variables for 5MTP

<table>
<thead>
<tr>
<th></th>
<th>5MTP\textsubscript{intact} (n=64)</th>
<th>5MTP\textsubscript{impaired} (n=28)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>95% CI</td>
</tr>
<tr>
<td>AGE</td>
<td>64</td>
<td>66.6 (14.2)</td>
<td>63.12-70.08</td>
</tr>
<tr>
<td>LOS</td>
<td>64</td>
<td>36.4 (24.5)</td>
<td>30.4-42.4</td>
</tr>
<tr>
<td>DPOST</td>
<td>64</td>
<td>16.0 (11.7)</td>
<td>13.13-18.87</td>
</tr>
<tr>
<td>CMSA\textsubscript{foot}</td>
<td>60</td>
<td>4.07 (1.43)</td>
<td>3.71-4.43</td>
</tr>
<tr>
<td>CMSA\textsubscript{leg}</td>
<td>60</td>
<td>4.40 (1.21)</td>
<td>4.09-4.71</td>
</tr>
</tbody>
</table>
Mean, standard deviation (SD) and 95% confidence intervals for demographic and clinical variables for 5MTP\textsubscript{impaired} and 5MTP\textsubscript{intact} groups. The patient population was separated into intact (5MTP\textsubscript{intact}) and impaired (5MTP\textsubscript{impaired}) based on normative cutoffs. T-test was performed to identify group differences. (**) indicates statistical significance.

3.2 Relationships between plantar sensation and balance and gait

Spearman correlations for each 5MTP and HEEL sensation scores and the balance and gait measures of interest were performed. Presented in Tables 4 and 5 are the significant correlations before and after correcting for multiple comparisons using the Holm Method.

Table 4: HEEL Spearman Correlation results

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Correlation Coefficient (r)</th>
<th>p-value</th>
<th>Adjusted Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBS</td>
<td>92</td>
<td>-0.33</td>
<td>0.0015</td>
<td>0.0026**</td>
</tr>
<tr>
<td>RMS\textsubscript{MLtot}</td>
<td>86</td>
<td>0.325</td>
<td>0.0023</td>
<td>0.00278**</td>
</tr>
<tr>
<td>RQ\textsubscript{AP}</td>
<td>86</td>
<td>0.307</td>
<td>0.0041</td>
<td>0.0029</td>
</tr>
<tr>
<td>Velocity</td>
<td>65</td>
<td>-0.312</td>
<td>0.0115</td>
<td>0.0031</td>
</tr>
<tr>
<td>RMS\textsubscript{APtot}</td>
<td>86</td>
<td>0.221</td>
<td>0.0407</td>
<td>0.0033</td>
</tr>
<tr>
<td>CMSA\textsubscript{foot}</td>
<td>85</td>
<td>-0.222</td>
<td>0.0409</td>
<td>0.0036</td>
</tr>
<tr>
<td>CMSA\textsubscript{leg}</td>
<td>85</td>
<td>-0.213</td>
<td>0.0505</td>
<td>0.0038</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>Correlation Coefficient (r)</td>
<td>p-value</td>
<td>Adjusted Alpha</td>
</tr>
<tr>
<td>----------</td>
<td>----</td>
<td>-----------------------------</td>
<td>---------</td>
<td>----------------</td>
</tr>
<tr>
<td>BBS</td>
<td>90</td>
<td>-0.305</td>
<td>0.0035</td>
<td>0.0026</td>
</tr>
<tr>
<td>RQ_{AP}</td>
<td>84</td>
<td>0.296</td>
<td>0.0062</td>
<td>0.0028</td>
</tr>
<tr>
<td>CMSA_{foot}</td>
<td>83</td>
<td>-0.242</td>
<td>0.0272</td>
<td>0.0029</td>
</tr>
<tr>
<td>RMS_{MLtot}</td>
<td>84</td>
<td>0.241</td>
<td>0.0275</td>
<td>0.0031</td>
</tr>
<tr>
<td>Age</td>
<td>90</td>
<td>0.229</td>
<td>0.0297</td>
<td>0.0033</td>
</tr>
</tbody>
</table>
Spearman correlation results for the relationship between sensation at the 5MTP testing site and balance and gait variables of interest. The Holm method was applied to account for the multiple comparisons. Variables are ordered by increased p-values as per this method. The resulting adjusted significance level is also presented. (**) indicates statistical significance.

A significant negative relationship exists between HEEL and BBS (r=-0.326, p=0.0015). HEEL and RMSMLtot have a significant positive relationship (r=0.325, p=0.0023). These relationships are illustrated in Figures 1 and 2. There were a number of variables associated with HEEL including RQAP (p=0.0041), Velocity (p=0.0115), RMSAPtot (p=0.0407) and CMSAfoot (p=0.0409), though these relationships did not meet the adjusted significance level after correcting for multiple comparisons. For 5MTP,

<table>
<thead>
<tr>
<th></th>
<th>90</th>
<th>0.225</th>
<th>0.0327</th>
<th>0.0036</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>90</td>
<td>0.225</td>
<td>0.0327</td>
<td>0.0036</td>
</tr>
<tr>
<td>RMSAPtot</td>
<td>84</td>
<td>0.228</td>
<td>0.0369</td>
<td>0.0038</td>
</tr>
<tr>
<td>RMSMLload</td>
<td>83</td>
<td>0.215</td>
<td>0.0514</td>
<td>0.0042</td>
</tr>
<tr>
<td>%BWquietEC</td>
<td>84</td>
<td>0.189</td>
<td>0.0851</td>
<td>0.0045</td>
</tr>
<tr>
<td>RQML</td>
<td>84</td>
<td>0.178</td>
<td>0.105</td>
<td>0.005</td>
</tr>
<tr>
<td>Rstep</td>
<td>64</td>
<td>0.184</td>
<td>0.146</td>
<td>0.0056</td>
</tr>
<tr>
<td>%BWload</td>
<td>83</td>
<td>-0.154</td>
<td>0.165</td>
<td>0.0063</td>
</tr>
<tr>
<td>CMSAleg</td>
<td>83</td>
<td>-0.149</td>
<td>0.176</td>
<td>0.0071</td>
</tr>
<tr>
<td>SI</td>
<td>84</td>
<td>-0.128</td>
<td>0.246</td>
<td>0.0083</td>
</tr>
<tr>
<td>Velocity</td>
<td>64</td>
<td>-0.137</td>
<td>0.279</td>
<td>0.01</td>
</tr>
<tr>
<td>RMSAPload</td>
<td>83</td>
<td>0.1</td>
<td>0.367</td>
<td>0.013</td>
</tr>
<tr>
<td>%BWstand</td>
<td>84</td>
<td>0.0695</td>
<td>0.53</td>
<td>0.017</td>
</tr>
<tr>
<td>Rswing</td>
<td>64</td>
<td>0.0704</td>
<td>0.58</td>
<td>0.023</td>
</tr>
<tr>
<td>DPOST</td>
<td>90</td>
<td>0.00189</td>
<td>0.986</td>
<td>0.05</td>
</tr>
</tbody>
</table>
there were no significant associations with any of the balance and gait variables of interest. However there were some associations that were significant before the adjustment for multiple comparisons was applied including BBS ($r= -0.305$, $p=0.0035$), RQ$_{AP}$ ($r=0.296$, $p=0.0062$), CMSA$_{foot}$ ($r=-0.242$, $p=0.0272$), RMS$_{MLtot}$ ($r=0.241$, $p=0.0275$), Age ($r=2.29$, $p=0.0297$), LOS ($r=0.225$, $p=0.0327$) and RMS$_{APtot}$ ($r=0.228$, $p=0.0369$).

**Figure 1: Spearman Correlation for HEEL and Berg Balance Scale scores**

*HEEL sensation is negatively correlated ($r=-0.326$) with Berg Balance score (BBS) ($p=0.0015$).*

*Heel scores increase (level of sensation decreases), BBS scores decrease (postural instability increases). The vertical line represents the trending relationship in the dataset.*
Figure 2: Spearman Correlation for HEEL and RMS\textsubscript{MLtot}

HEEL sensation is positively correlated \((r=0.325)\) with postural sway \((\text{RMS}_{\text{MLtot}})\) \((p=0.0023)\).

HEEL sensation scores increase alongside an increase in the magnitude in ML sway. The vertical line represents the trending relationship in the dataset.

3.3 Research Objective Results

The results for comparisons of balance and gait variables of interest between HEEL\textsubscript{intact} and HEEL\textsubscript{impaired}, and between 5MTP\textsubscript{intact} and 5MTP\textsubscript{impaired} are presented separately for each research objective. Included in each section are summary tables presenting the results of the ANCOVAs, with CMSA\textsubscript{foot} as a covariate, and multiple comparison correction. The variables have been ordered by increasing p-values, as required by the Holm Method.
3.3.1 Research Objective 1: Plantar sensation and standing balance control

3.3.1.1 Heel sensation

The RMS\textsubscript{APtot} and RMS\textsubscript{MLtot} values were greater in HEEL\textsubscript{impaired} compared to HEEL\textsubscript{intact} (F(2, 76)= 16.15, p=0.0001, \(\eta^2=0.17\); F(2, 76)= 21.65, \(\eta^2=0.2\), respectively). BBS were lower in HEEL\textsubscript{impaired} compared to HEEL\textsubscript{intact} (F(2, 82)= 8.59, p=0.0044, \(\eta^2=0.047\)). RMS\textsubscript{MLload} was significantly different before applying the correction procedure (F(2, 75)= 4.26, p=0.0425, \(\eta^2=0.048\)) but not after. The group means for the HEEL\textsubscript{impaired} and HEEL\textsubscript{intact} groups are illustrated in Figures 3-5.

Table 6: ANCOVA results for HEEL and balance variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>HEEL\textsubscript{intact}</th>
<th>HEEL\textsubscript{impaired}</th>
<th>HEEL ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Mean (SD)</td>
<td>N</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td>RMS\textsubscript{MLtot}</td>
<td>50 3.41 (2.11)</td>
<td>36 5.87 (3.20)</td>
<td>21.65</td>
</tr>
<tr>
<td>RMS\textsubscript{APtot}</td>
<td>50 5.65 (2.08)</td>
<td>36 7.79 (3.3)</td>
<td>16.15</td>
</tr>
<tr>
<td>BBS</td>
<td>51 37.7 (18.5)</td>
<td>41 25.9 (17.3)</td>
<td>8.59</td>
</tr>
<tr>
<td>RMS\textsubscript{MLload}</td>
<td>50 7.36 (3.66)</td>
<td>35 9.62 (5.88)</td>
<td>4.26</td>
</tr>
<tr>
<td>RMS\textsubscript{APload}</td>
<td>50 7.67 (3.17)</td>
<td>35 9.05 (3.58)</td>
<td>3.07</td>
</tr>
<tr>
<td>%BW\textsubscript{load}</td>
<td>50 76.3 (9.54)</td>
<td>35 71.2 (17.7)</td>
<td>2.11</td>
</tr>
<tr>
<td>SI</td>
<td>50 0.565 (0.11)</td>
<td>36 0.563 (0.12)</td>
<td>1.55</td>
</tr>
<tr>
<td>%BW\textsubscript{quiet}</td>
<td>50 47.4 (7.1)</td>
<td>36 47.1 (10.9)</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Results of ANCOVA between HEEL\textsubscript{impaired} and HEEL\textsubscript{intact} for variables of standing balance. The Holm Method was applied to account for multiple comparisons and variables are ordered by
increased p-values as per this method. The resulting adjusted significance level is also presented.
Postural sway was higher in both $\text{RMS}_{\text{APtot}} (p<0.0001)$ and $\text{RMS}_{\text{MLtot}} (p=0.0001)$, and BBS was lower ($p=0.0044$) for HEEL\text{impaired}. (***) indicates statistical significance.

![Figure 3: Mean $\text{RMS}_{\text{MLtot}}$ for HEEL groups.](image)

Results for differences in $\text{RMS}_{\text{MLtot}}$ between HEEL\text{impaired} and HEEL\text{intact}. HEEL\text{impaired} had significantly greater ML sway ($F= 21.65, p<0.0001$). Error bars represent the standard deviation (SD). (***)indicates statistical significance
Results for differences in RMS$_{AP_{tot}}$ between HEEL$_{impaired}$ and HEEL$_{intact}$. HEEL$_{impaired}$ had significantly greater AP sway ($F = 16.15, p = 0.0001$). Error bars represent the standard deviation (SD). (**) indicates statistical significance.

Results for differences in BBS between HEEL$_{impaired}$ and HEEL$_{intact}$. HEEL$_{impaired}$ had significantly lower Berg Balance scores ($F = 8.59, p = 0.0044$). Error bars represent the standard deviation (SD). (**) indicates statistical significance.
3.3.1.2  5MTP sensation

After correcting for multiple comparisons, there were no differences found between 5MTP\textsubscript{intact} and 5MTP\textsubscript{impaired}. There were some relationships that were significant before correction such as RMS\textsubscript{APtot} (F(2, 76)=6.85, p=0.0107, $\eta^2$=0.08), RMS\textsubscript{MLtot} (F(2, 76)= 5.82, p=0.0183, $\eta^2$=0.02), and %BW\textsubscript{quiet} (F(2, 76)=4.18, p= 0.444, $\eta^2$=0.04).

**Table 7: ANCOVA results for 5MTP and balance variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>5MTP\textsubscript{intact}</th>
<th>5MTP\textsubscript{impaired}</th>
<th>5MTP ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>N</td>
</tr>
<tr>
<td>RMS\textsubscript{APtot}</td>
<td>61</td>
<td>6.02 (2.39)</td>
<td>25</td>
</tr>
<tr>
<td>RMS\textsubscript{MLload}</td>
<td>61</td>
<td>7.55 (3.87)</td>
<td>24</td>
</tr>
<tr>
<td>%BW\textsubscript{quiet}</td>
<td>61</td>
<td>46.35 (9.33)</td>
<td>25</td>
</tr>
<tr>
<td>SI</td>
<td>61</td>
<td>0.575 (0.12)</td>
<td>25</td>
</tr>
<tr>
<td>%BW\textsubscript{load}</td>
<td>61</td>
<td>75.35 (10.2)</td>
<td>24</td>
</tr>
<tr>
<td>RMS\textsubscript{MLtot}</td>
<td>61</td>
<td>4.14 (2.9)</td>
<td>25</td>
</tr>
<tr>
<td>BBS</td>
<td>64</td>
<td>34.47 (18.3)</td>
<td>28</td>
</tr>
<tr>
<td>RMS\textsubscript{APload}</td>
<td>61</td>
<td>8.02 (3.28)</td>
<td>24</td>
</tr>
</tbody>
</table>

Results of ANCOVA between 5MTP\textsubscript{impaired} and 5MTP\textsubscript{intact} for variables of standing balance. The Holm Method was applied to account for multiple comparisons and variables are ordered by increased p-values as per this method. The resulting adjusted significance level is also presented.

There were no significant differences between the groups.
3.3.2 Research Objective 2: Plantar sensation and gait

3.3.2.1 Heel Sensation

Velocity is slower in the HEEL_{impaired} group compared to HEEL_{intact} (F(2, 57)=5.72, p=0.0201, \( \eta^2 = 0.07 \)), but did not meet the adjusted significance level of 0.0167. Group means for R_{swing} and R_{step} were not found to be significantly different between the HEEL_{impaired} and HEEL_{intact} groups (F(2, 57)=3.94, p=0.052, \( \eta^2 = 0.055 \), and F(2, 57)=3.3, p=0.0744, \( \eta^2 = 0.05 \), respectively). Results are presented in Table 8.

Table 8: ANCOVA results for HEEL and gait variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>HEEL_{intact}</th>
<th>HEEL_{impaired}</th>
<th>HEEL ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>N</td>
</tr>
<tr>
<td>Velocity</td>
<td>40</td>
<td>76.6 (33.4)</td>
<td>25</td>
</tr>
<tr>
<td>R_{swing}</td>
<td>40</td>
<td>1.09 (0.13)</td>
<td>25</td>
</tr>
<tr>
<td>R_{step}</td>
<td>40</td>
<td>1.08 (0.08)</td>
<td>25</td>
</tr>
</tbody>
</table>

Results of ANCOVA for HEEL_{impaired} and HEEL_{intact} for variables of gait. The Holm Method was applied to account for multiple comparisons and variables are ordered by increased p-values as per this method. The resulting adjusted significance level is also presented. There were no significant differences between the groups.
3.3.2.2 5MTP Sensation

For 5MTP (Table 9), there were no significant differences in velocity
\((F(2,57)=0.06, p=0.808, \eta^2=0.0008)\), \(R_{\text{swing}}\) \((F(2, 57)=0.56, p=0.459, \eta^2=0.008)\) or \(R_{\text{step}}\)
\((F(2, 57)=0.96, p=0.333, \eta^2=0.015)\) between the 5MTPimpaired and 5MTP \(_{\text{intact}}\) groups
before applying any correction methods.

**Table 9: ANCOVA results for 5MTP and gait variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>5MTP(_{\text{intact}})</th>
<th>5MTP(_{\text{impaired}})</th>
<th>5MTP ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{\text{step}})</td>
<td>47</td>
<td>1.09 (0.1)</td>
<td>18</td>
</tr>
<tr>
<td>(R_{\text{swing}})</td>
<td>47</td>
<td>1.14 (0.21)</td>
<td>18</td>
</tr>
<tr>
<td>Velocity</td>
<td>47</td>
<td>69.5 (34.4)</td>
<td>18</td>
</tr>
</tbody>
</table>

Results of ANOCOVA for 5MTPimpaired and 5MTPintact for variables of gait. The Holm
Method was applied to account for multiple comparisons and variables are ordered by increased
\(p\)-values as per this method. The resulting adjusted significance level is also presented. There
were no significant differences between the groups.
3.3.3 Research Objective 3: Plantar sensation, vision and control of posture

3.3.3.1 Heel sensation

There were no significant differences present between HEEL\textsubscript{impaired} and HEEL\textsubscript{intact} (Table 10) for $\%BW\textsubscript{quietEC}$ ($F(2, 76)=1.52, p=0.221$), RQ\textsubscript{AP} ($F(2, 76)=0.76, p=0.385$), or RQ\textsubscript{ML} ($F(2, 76)=0.1, p=0.757$).

Table 10: ANCOVA results for HEEL and vision variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>HEEL\textsubscript{intact}</th>
<th>HEEL\textsubscript{impaired}</th>
<th>HEEL ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>N</td>
</tr>
<tr>
<td>%BW\textsubscript{quietEC}</td>
<td>50</td>
<td>47.2 (7.76)</td>
<td>36</td>
</tr>
<tr>
<td>RQ\textsubscript{AP}</td>
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<td>1.29 (0.39)</td>
<td>36</td>
</tr>
<tr>
<td>RQ\textsubscript{ML}</td>
<td>50</td>
<td>1.28 (0.53)</td>
<td>36</td>
</tr>
</tbody>
</table>

Results of ANCOVA for HEEL\textsubscript{impaired} and HEEL\textsubscript{intact} for variables related to vision. The Holm Method was applied to account for multiple comparisons and variables are ordered by increased p-values as per this method. The resulting adjusted significance level is also presented.

There were no significant differences between the groups
3.3.3.2 5MTP Sensation

When comparing 5MTP\textsubscript{impaired} and 5MTP\textsubscript{intact} (Table 11), there was a difference found in $\%\text{BW}_{\text{quietEC}}$ ($F(2, 76) = 6.81, p = 0.0109, \eta^2 = 0.07$) that did meet the adjusted significance level of 0.0167. This relationship is illustrated in Figure 6. No differences were present for RQ\textsubscript{AP} ($F(2, 76) = 1.99, p = 0.163, \eta^2 = 0.025$) and RQ\textsubscript{ML} ($F(2, 76) = 0.12, p = 0.732, \eta^2 = 0.0015$).

Table 11: ANCOVA results for 5MTP and vision variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>5MTP\textsubscript{intact}</th>
<th>5MTP\textsubscript{impaired}</th>
<th>5MTP ANCOVA results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (SD)</td>
<td>N</td>
</tr>
<tr>
<td>$%\text{BW}_{\text{quietEC}}$</td>
<td>61</td>
<td>46.3 (9.34)</td>
<td>25</td>
</tr>
<tr>
<td>RQ\textsubscript{AP}</td>
<td>61</td>
<td>1.31 (0.42)</td>
<td>25</td>
</tr>
<tr>
<td>RQ\textsubscript{ML}</td>
<td>61</td>
<td>1.37 (0.84)</td>
<td>25</td>
</tr>
</tbody>
</table>

Results of ANCOVA for 5MTP\textsubscript{impaired} and 5MTP\textsubscript{intact} for variables related to vision. The Holm Method was applied to account for multiple comparisons and variables are ordered by increased $p$-values as per this method. The resulting adjusted significance level is also presented. There is a higher percentage of weight borne over the paretic limb with eyes closed ($\%\text{BW}_{\text{quietEC}}$) in the 5MTP\textsubscript{impaired} group compared to 5MTP\textsubscript{intact} ($p = 0.0109$).
Figure 6: Mean $\%\text{BW}_{\text{quietEC}}$ for 5MTP groups.

Results for differences between 5MTPimpaired and 5MTPintact in $\%\text{BW}_{\text{quietEC}}$. The 5MTPimpaired group bore a higher percentage of weight over their paretic limb compared to 5MTPintact ($F=6.81, p=0.0109$). Error bars represent the standard deviation (SD). (**) indicates statistical significance
Chapter 4

4 Discussion

The aim of this study was to examine the relationship between plantar sensation and standing balance and gait function after stroke. This study examined these relationships in individuals with stroke who underwent testing shortly after admission to an inpatient stroke rehabilitation program. The results of this study suggest that a relationship exists between impaired plantar sensation on the affected side and some aspects of postural instability during standing. Impaired sensation does not appear related to gait velocity or spatiotemporal gait asymmetry. Finally, plantar sensation deficits are not related to the overuse of vision as a compensatory strategy for the control of quiet standing. These are potentially important findings though it should be noted that the impact of impaired plantar sensation on standing balance occurs in the presence of other factors (e.g. proprioception, muscle strength). However, this study does suggest that plantar sensation should be considered when assessing the potential underlying causes of instability in standing in individuals post stroke.

Other factors that play a role in postural control of quiet standing and gait include motor impairment, age, comorbidities and impaired cognitive function. The current study was able to account for some of these factors. CMSAfoot scores in the HEEL-impaired group were lower indicating a greater level of motor impairment. This was accounted for by using CMSAfoot as a covariate in the analysis, controlling for its influence on the gait and standing balance variables of interest. There are also factors other than stroke that influence plantar sensation including diabetes and age. Those with diabetes were
excluded from the analysis, as this group may present with potentially confounding sensory deficits and related functional impairments in standing balance and gait (Kanade, Van Deursen, Robert William Martin, Harding, & Price, 2008; Meyer et al., 2004). Age related decline in sensation was also accounted for by using different normative cutoffs for impaired vs. intact sensation for the 35-64, and 65+ age groups. Thus it is reasonable to assume that the results of this study accurately reflect the relationship between plantar sensation of the affected foot and standing balance and gait post-stroke. This chapter will provide a general description of the study group followed by a discussion of the results for each of the research objectives separately.

4.1 Deficits in Plantar Sensation Post-stroke

Some individuals with stroke included in this study had decreased plantar sensation in their affected foot as measured by monofilament testing and compared to age-matched normative threshold values for protective sensation (Plucknette et al., 2012). Forty-five percent of the group exhibited sensation deficits at the heel and 30% exhibited deficits at the 5th metatarsal head. Comparison to previous literature is difficult because of differences in the type of sensation tested (e.g. proprioception versus tactile sensation), the method used to test sensation (e.g. monofilaments, performance-based scales), the body part tested (e.g. sole of the foot, ankle) and the aspect of sensation tested (e.g. detection versus discrimination). However, in the study most similar to the current study, Tyson and colleagues (2008) conducted tests of detection and discrimination abilities for proprioception and tactile sensation in both the arm and the leg of individuals admitted to
an inpatient stroke rehabilitation program. They reported that 41% of individuals exhibited deficits in detection of a tactile stimulus to the foot (Tyson et al., 2008). Individuals in the Tyson study (2008) were tested between 2 and 4 weeks after stroke. The minimum end of that range roughly relates to the mean time post stroke for the current study, which was 17 days. Thus, plantar sensation loss appears to be an issue for approximately 30-40% of individuals in the subacute phase of stroke admitted to an inpatient rehabilitation program.

4.2 Quiet Standing Balance and Gait Deficits Post Stroke

The entire study group exhibited deficits in quiet standing balance. Published values for RMS COP displacement in the anteroposterior and mediolateral directions for healthy adults range from 3.49 (1.11) to 3.98 (1.22) mm and 2.07 (0.87) to 2.54 (1.34) mm respectively (Maki, Holliday, & Topper, 1994; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). The group means for the current study were greater than the upper end of these ranges by approximately 2mm. Therefore, the individuals with stroke in this study had instability in quiet standing in both the anteroposterior and mediolateral directions. This is similar to previous findings by de Haart and coauthors who reported instability in standing in both directions in a subacute stroke population measured with RMS of COP velocity (de Haart et al., 2004).

The current study also found weight bearing on the non-paretic limb for the whole group to be towards the low end of an estimated range for healthy adults. Weight bearing
under one limb in healthy adults during quiet standing has been conservatively estimated to be 47–53% (Mansfield et al., 2013). The study group in this study bore 47.3 (8.8)% of their body weight on the paretic limb.

Decreased gait velocity and spatiotemporal asymmetry are well documented after stroke. The group tested in this study exhibited both of these gait deviations. Reports of preferred pace gait velocity in the subacute stage range from 13 cm/s to 65 cm/s (Bale & Strand, 2008; Bohannon, 1987). This is significantly slower than the gait velocity reported for healthy older adults. For example, Patterson and coauthors (2012) reported a preferred gait velocity of 113.79 (23.34) cm/s for a group of 81 healthy older adults with a mean age of 64.2 (22.4) years. Steffen and colleagues (2002) reported preferred gait velocity by age and gender; velocities reported for men and women between 60-69 years were 1.59 (0.24) cm/s and 1.44 (0.25) cm/s respectively. The current study group, with a mean age of 67.9 (13.2) years, had a mean preferred velocity of 67.79 (32.54) cm/s. This approximates the upper range of reported values for individuals with subacute stroke and falls well below the reported values for healthy older adults.

The group in this study was also spatially and temporally asymmetric. The mean step symmetry (1.10(0.10)) and swing symmetry (1.16(0.27)) were above the cut-offs for symmetric gait (1.08 for step symmetry and 1.06 for swing symmetry) (Patterson et al., 2010b). The mean symmetry ratios for this study were slightly less than those reported for individuals with chronic stroke by Patterson and colleagues. They reported mean step length and swing time symmetry ratios for a group of individuals with chronic stroke as 1.13 (0.20) and 1.24 (0.34) respectively (Patterson et al., 2010b). However, previous work has demonstrated the potential for gait asymmetry to get worse after rehabilitation
(Patterson et al., 2010a). This was a cross-sectional study and although means and standard deviations were not reported, the figures indicate that individuals 0 to 3 months post stroke (within the time frame of this study group) had approximate step and swing ratios of 1.10 and 1.20 respectively.

4.3 The use of vision as a compensatory strategy for instability

As a whole, the study group exhibited an over-reliance on vision to control quiet standing since the Romberg quotient values for both anteroposterior (1.35 (0.42)) and mediolateral (1.38 (0.76)) COP displacement were above those reported for healthy older adults (1.16 (0.36) and 1.12 (0.66) respectively) (Prieto et al., 1996). The over-use of vision to assist with postural control may happen with sensory loss (i.e. loss of plantar sensation) or an inability to select and integrate sensory input (Bonan et al., 2004). Bonan and coauthors have suggested that reliance on visual input may be a learned response that develops over time since there is no evidence for it immediately after stroke. However, the increased Romberg quotients in this study of individuals shortly after stroke suggests either that reliance on vision to control standing balance occurs around the time of the stroke incident or it is a strategy that is learned quickly in the first two weeks after stroke before rehabilitation occurs.
In summary, the group of individuals with subacute stroke had a typical clinical presentation. They exhibited instability in standing, walked slowly and asymmetrically and they relied on vision to control their upright standing posture.

4.4 Research Objective 1: Plantar sensation and standing balance control

Plantar sensation of the affected foot was significantly associated with functional performance measures and force plate measures of standing balance. Plantar sensation was negatively correlated with BBS scores indicating that individuals with better plantar sensation have better functional standing balance. In addition, plantar sensation at the heel was positively associated with centre of pressure displacement in the mediolateral direction. This indicates that those with greater cutaneous sensory impairment were more unstable in the mediolateral direction. Finally, group comparisons revealed that individuals with impaired sensation at the heel had worse functional balance (as measured by BBS) and greater postural sway in both the mediolateral and anteroposterior directions. These results coincide with previous work, in which chronic stroke patients were more unstable in the mediolateral direction (Marigold & Eng, 2006).

During quiet standing, pressure on the plantar aspect of the feet stimulates skin receptors in the soles of the feet (Zhang & Li, 2013). This cutaneous sensory information from the feet may be used by the balance control system to guide the generation of forces applied to the ground, weight transfer between the lower limbs and provide information
regarding features of the support surface (Meyer et al., 2004; Zhang & Li, 2013). In the case of sensory loss after stroke, this information is not available to guide force production in the anteroposterior direction and weight shifting between the paretic and non-paretic limbs in the mediolateral direction and hence these movements may be uncoordinated or poorly executed. This may have led to the increased COP displacement in both directions observed in individuals with sensory loss in this study.

4.5 Research Objective #2: Plantar Sensation and Gait

Contrary to the hypotheses, this study found no significant association between plantar sensation and either velocity or spatiotemporal symmetry of gait. There are two possible explanations for these results. First, it is possible that other types of sensation, such as proprioception, are more important for the control of velocity and spatiotemporal symmetry of gait and plantar cutaneous sensation does not play a role. Second, plantar sensation may not be involved in the control of the speed or symmetry of steady state walking, but it may be a factor in the control of other aspects of gait such as the variability of step length and step time or in the control of other walking conditions such as fast walking, gait termination or walking over uneven surfaces. These two possible explanations for the study results will be discussed in more detail.

Plantar sensation may have a greater role in the control of standing balance than steady state gait. Zhang and coauthors (2013) found a limited role for plantar sensation in the control of gait in individuals with peripheral neuropathy. The authors investigated the
relationship between sensation in the foot and pressure distribution patterns at the foot (which correlates with plantar sensation) during treadmill walking and during quiet standing (Zhang & Li, 2013). Reduced plantar sensation was related to greater pressure placed at the heel in standing but was not associated with changes in pressure distribution at the foot during gait (Zhang & Li, 2013). The authors concluded that plantar sensation may not have important role during gait due to the way gait is controlled. Compared to quiet standing, which relies on feedback control, gait depends on feedforward control, which does not require sensory input (Zhang & Li, 2013).

The results of this study and those of Zhang suggest that sensation does not play a large role in walking. There are many other mechanisms that may have a larger, more important role for the control of gait. A number of previous studies have found changes in gait are mainly due to deficits in motor impairment. A study on mild to moderate stroke patients determined that muscle strength of the hip and knee flexors was the largest contributor to comfortable and fast gait velocities, second being the spasticity of the ankle plantar flexors and third being sensation (Hsu et al., 2003). Although the authors calculated that sensation was the 3rd largest contributor to gait velocity, they state that the role of muscle strength and spasticity are of much more importance. The same study goes on to state that the factors most largely associated with temporal and spatial asymmetry are, in order; 1) spasticity of ankle plantar flexors, 2) motor function of the affected lower limb, and 3) sensation. It is important to note that Hsu’s study utilized the Fugl-Meyer Assessment as its measure of sensation which groups cutaneous sensation and proprioception together in one score. Though the study found sensation to be of
moderate importance for gait, it may be that proprioception may have a larger role compared to cutaneous sensation.

The second explanation for the non-significant results of this study is that cutaneous sensation may be related to other states of walking or other gait parameters that were not examined. The contribution of plantar sensation to the control of gait may depend on the phase of the gait cycle. Walking produces a large amount of cutaneous sensory input from the foot as it contacts the ground and from the skin when it is stretch during movements of the lower limbs (Duysens et al., 1995). Given the fact most of this sensory information is repetitive and largely predictable, it is possible that not all of it needs to be processed or even utilized in the control of gait. Instead, there may be specific points in the gait cycle where sensation is used more for the control of walking. Duysens and colleagues (1995) studied the regulation or gating of sensory information during walking by testing the intensity of sensory input from the foot reported by healthy adults during standing and at different phases of the gait cycle. They found that in general there is an increase in the threshold for perception of sensory stimuli from the foot during walking (Duysens et al., 1995). In other words, people are less sensitive to touch at the foot during walking compared to standing. However, there were specific points in the gait cycle where there was a relative increase or decrease in sensitivity to touch. Sensitivity to touch was lowest just after heel contact and highest just prior to heel contact (Duysens et al., 1995). These results suggest that the transmission of cutaneous input from the foot to the brain during single limb stance phase is decreased and thus is not used in the control of this gait phase, which relates to swing symmetry. In addition, sensation is decreased at the end of stance when push off occurs. Since the propulsive force
generated at the end of stance contributes to gait velocity and sensitivity is decreased at this point of the gait cycle, it seems that cutaneous sensation does not contribute to the control of velocity either. Duysens and colleagues suggest that the increased sensitivity just prior to heel contact is functional. They suggest sensory information at this point of the gait cycle is used to guide foot placement for heel contact (Duysens et al., 1995).

There may be parameters of gait that are affected by plantar sensation but were not measured in this study. It is possible that a relationship exists between plantar sensation and gait variability or step width. Alternatively, plantar sensation may also be more important for other walking conditions such as fast walking, gait termination or walking over uneven terrains. For example, Perry and coauthors (2001) examined the effects of reduced plantar sensation on gait termination (defined as the final 2 steps after steady/consistent pace gait) in healthy adults. They induced plantar sensation loss with an ice bath and then measured the kinematics and kinetics of gait termination. Perry and coauthors found that plantar sensation is important for providing information regarding the centre of mass movement during single stance phase and in guiding the placement of the foot to apply breaking forces. In addition, Nadeau and coauthors (1999) found that sensation in the lower limb (measured by the Fugl-Meyer) was an important variable to predict fast but not preferred walking speed in individuals with stroke.

This section concludes that in general there may be a larger role of proprioception and muscle strength in the control of gait than plantar cutaneous sensation. Plantar sensation is not needed for the control of gait velocity or spatiotemporal symmetry, however it may have a role in guiding foot placement and during gait termination.
4.6 Research Objective #3: Plantar sensation and compensation of vision for controlling upright posture

It was hypothesized that plantar sensation deficits would be associated with using vision as a compensation for controlling posture as measured by the Romberg Quotient and decreased weight bearing on the paretic limb when the eyes were closed. Contrary to the hypothesis, this study found no difference in Romberg quotients between the impaired and intact sensory groups. In addition, this study found that the impaired 5MTP group bore a greater percentage of their body weight over their paretic limb (50.6%) compared to the intact group (46.1%) when their eyes were closed. It is important to note that the impaired sensory group was not loading the paretic limb preferentially but were actually more symmetrical in the distribution of weight between the two limbs in standing. Mansfield and coauthors (2013) examined asymmetric weight bearing during quiet stance with eyes open in a group of individuals with chronic stroke. They found that 88% of their sample had increased weight bearing on the non-paretic limb compared to a normal range of loading (47–53% of body weight). In this study of individuals with subacute stroke, the impaired sensory group was within “normal” limits for weight bearing in standing and the intact group was not. This was during an eyes closed condition. However, the weight-bearing values during the eyes open condition show the same trend; the impaired sensory group exhibited weight bearing within the normal range (49.5%) and the intact group did not (46.3%). It was hypothesized that individuals with impaired sensation would weight their non-paretic limb more due to the comfort or sense of stability they might feel. The results of this study suggest this is not the case. It is
possible that those with impaired sensation may not be aware of the increased instability and hence do not use the compensation of weighting their non-paretic limb more than the intact sensation group. It is also possible that this group placed more weight on their paretic limb (compared to the intact sensory group) in order to increase the intensity of the stimulation of the sensory receptors of the foot in an effort to get more sensory information from that impaired limb.

The entire study group had increased Romberg quotients compared to healthy adults indicating the use of vision as a compensation for poor standing balance. However, this study found no difference in the Romberg quotients between the impaired and intact groups for either sensory testing location. Therefore, impaired plantar sensation does not mean greater reliance on vision as compensation. It has been proposed that vision as compensation may be a learned mechanism over time, after the acute stage of stroke, and that it is a strategy used to correct for poor balance in general, and not due to any specific impairment (such as cutaneous sensation) (Bonan et al., 2004). If this is the case, then both the impaired and intact sensation groups learned this compensation quickly before rehabilitation had commenced since this study analyzed balance assessments taken at admission.

4.7 Limitations

The current study has several limitations, which restrict the generalization to the larger stroke population. First, this study used balance and gait assessment values taken
at admission to an inpatient stroke rehabilitation program. It is possible that the relationship between plantar sensation and balance and gait may change as individuals recover. Second, this study excluded individuals who could not stand unsupported for 30 seconds. Given the time frame of the assessment (i.e. at admission) it is likely that many individuals did not meet this inclusion criterion. Therefore the results of this study may only apply to higher functioning individuals. Furthermore, it could be argued that there was a risk for false negative findings given the adjustments made for multiple comparisons. This issue was addressed by using the Holm method which is less conservative than other methods, (e.g. Bonferonni method) however false negative findings could still be possible. There could be concern about the fact that this study was a retrospective chart review. However, it is likely that this is not of great concern since all the data were collected from the same on-site clinic that follows a standardized assessment protocol.

One final limitation that should be noted is the cutoffs for protective sensation used to divide the individuals in this study into the intact and impaired groups. These cutoffs were used because they accounted for age, were specific to the plantar aspect of the foot and provided an objective method to judge sensory impairment. However, these cutoffs were developed for use in the diabetic population and represent the level of plantar sensation required to recognize pressure applied to the foot that could lead to foot ulcers. It is possible that the level of cutaneous sensation required to control standing balance and gait is represented by a much lower threshold. If this is the case, then individuals identified as having intact sensation in this study may have had some sensory loss that could affect balance and gait. Therefore these individuals may have biased the
balance and gait measures of interest for the intact sensory group to be more impaired which in turn would have made finding a difference between the intact and impaired sensory groups less likely.

4.8 Implications

The results of this study have implications for rehabilitation after stroke. First, it suggests that plantar cutaneous sensation should be assessed in individuals in stroke rehabilitation. If there are sensory impairments revealed by an assessment this would suggest that the individual may have instability in standing. If a patient has plantar sensation deficits the therapist may consider plantar cutaneous sensory training as a component of the rehabilitation program for that individual. There is some evidence that sensory training can improve sensation and standing balance. Morioka and Yagi (2003) studied the effects of a ‘perceptual learning task’ in people with stroke in a randomized controlled trial. Individuals with stroke randomized to the experimental group trained 5 days a week for 2 weeks in determining the hardness of 3 different standing surfaces with the soles of their feet. Both groups received standard rehabilitation during the study. The experimental group improved in their scores on the perceptual learning task and compared to the control group, also had greater improvements on measures of postural sway. The results of the current study taken together with those reported by Marioka and Yagi suggests that assessment and intervention for plantar cutaneous sensation would be beneficial for individuals with stroke.
4.9 Future Directions

Future work should investigate the relationship between recovery of plantar cutaneous sensation and standing balance control after stroke in a longitudinal study. In addition, the relationship between cutaneous sensation and other gait parameters and gait conditions should be investigated. Furthermore, the relationship between plantar sensation and more complex postural control responses such as compensatory reactions to external perturbations could be examined. It is possible that plantar sensation has a role in the control of other features of gait and other components of balance control not examined in this study. This information could inform rehabilitation interventions and further support the regular inclusion of sensory assessment after stroke.
4.10 Conclusion and Summary

In conclusion, this study found a relationship between plantar cutaneous sensation in the affected foot and quiet standing balance after stroke. Individuals with stroke and impaired plantar sensation are less stable in the anteroposterior and mediolateral directions but they do not necessarily use vision as a compensation for this deficit. In contrast to standing balance, there does not appear to be a large role for plantar sensation in the control of the velocity and spatiotemporal symmetry of gait. The results of this study support the assessment of cutaneous sensory deficits in order to improve standing balance function after stroke.
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Curriculum Vitae

Name: Stephen Parsons

Post-secondary Education and Degrees:
University of Waterloo, Waterloo, Ontario, Canada
2006-2011, Honours, BSc.

Honours and Awards:
Western Graduate Research Scholarship
2012, 2013

Related Work Experience
Teaching Assistant- HS 2610
The University of Western Ontario
2012

Teaching Assistant- PT 9511
The University of Western Ontario
2012

Student Research Apprenticeship- KIN 391
The University of Waterloo
2010

Student Research Assistant
Division of Respiratory Medicine, Hospital for Sick Children, Toronto, ON
2009

Publications, Presentations and Abstracts:

Published Abstracts

Selected Oral Presentations
Parsons SL, Patterson KK. Validity and Accuracy of Accelerometers for Detecting Temporal Gait Parameters in Stroke Patients. Aging, Rehabilitation and Geriatric Care/Faculty of Health Science Symposium. February 2013.

Parsons SL, Patterson KK. Using accelerometers to measure gait asymmetry in the community. Western HRS Graduate Research Forum. February 2013.
Other Presentations