INFLUENCE OF LOWER EXTREMITY SENSORY FUNCTION ON THRESHOLD OF INTER-LIMB GAIT ASYMMETRY PERCEPTION IN PEOPLE POST STROKE

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ABSTRACT

Clinton Wutzke: Influence of Lower Extremity Sensation on Threshold of Inter-limb Gait Asymmetry Perception in People Post Stroke
(Under the direction of Michael D. Lewek)

People with chronic hemiparesis often walk with spatiotemporal asymmetry despite rehabilitation programs targeted to improve walking function. The persistence of walking asymmetry may be due, in part, to the perception of established walking patterns post stroke as ‘normal.’ As a result of perceiving this movement pattern as normal, people with chronic hemiparesis may therefore be unable to identify walking patterns that are more symmetrical. Also potentially contributing to this inability to perceive walking asymmetry are lower extremity sensory impairments. Although accurate afferent feedback is delivered to the central nervous system, inappropriate motor responses are produced leading to spatiotemporal asymmetry. The purpose of this study was to identify sensory impairments in the lower extremity of people with chronic hemiparesis and to determine associations between lower extremity sensation and perception of walking asymmetry in people with chronic hemiparesis.

Thirty people post stroke completed an assessment of lower extremity sensation including cutaneous, vibratory, and proprioceptive sensation of the paretic and non paretic limbs as well as walking on a split-belt treadmill under varying conditions of differences in speed between treadmill belts. Subjects responded when differences in speed between treadmill belts were perceived. Logistic regression models were used to determine thresholds of conscious perception and the spatiotemporal asymmetry ratios at the threshold of perception. Subconscious detection was determined as changes from baseline treadmill walking and walking with the belts moving at different speeds. Associations between the thresholds of conscious (awareness) and subconscious (detection) perception, spatiotemporal gait asymmetry (step length, stance time) ratios at thresholds of perception, and measures of lower extremity sensation were determined. It was found that cutaneous, vibratory, and proprioceptive differences in sensation exist between the paretic and non paretic lower limbs in people with chronic hemiparesis. Additionally, it was determined that magnitude of spatiotemporal asymmetry necessary for perception is greater than the gait asymmetry people post stroke typically walk with. Interestingly, individuals with overground step length or stance time asymmetry identify differences in speed between treadmill belts using step length or stance time respectively. However, sensation in the lower extremity of people post stroke did not appear to be associated with perception of walking asymmetry. Instead, perception of asymmetry was correlated with motor coordination of the lower extremity in people with chronic hemiparesis due to stroke.

These results suggest that individuals in the chronic stage following stroke have impairments in sensation in the lower extremity but these impairments are not associated with perception of walking asymmetry on a split-belt treadmill. Future studies should identify the components of motor coordination that contribute to the perception of walking asymmetry.

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CHAPTER 1:

INTRODUCTION

1.1 STROKE AND ITS INFLUENCE ON GAIT

Stroke is a leading cause of long-term disability in the United States as almost 800,000 people each year experience a stroke (Go et al. 2014). Following stroke, the lower extremity on the side contralateral to the brain lesion is typically more affected than the ipsilesional limb. The more affected "paretic" lower limb may exhibit impairments in strength (Andrews and Bohannon 2000), coordination (Tseng and Morton 2010), and/or sensation (Winward et al. 1999; Tyson et al. 2008). These impairments may have a functional consequence such as modified movement patterns that place greater dependency on the non-paretic lower limb during tasks such as walking (Raja et al. 2012).

Following stroke, rehabilitation programs are implemented to improve locomotor function (Silver et al. 2000; Hornby et al. 2008; Patterson et al. 2008a). Rehabilitation programs utilizing a variety of methods, including body weight supported walking (Visintin et al. 1998) and walking with robotic assistance (Hornby et al. 2008; Hidler et al. 2009; Westlake and Patten 2009) have improved walking speed. Despite improvements in walking speed, such paradigms have been unable to improve spatiotemporal symmetry in people post stroke (Patterson et al. 2008a). Locomotor rehabilitation programs have commonly attempted to minimize abnormal movement characteristics to produce a more functional walking pattern (Duncan et al. 2007; Hornby et al. 2008). However, minimizing asymmetry during treadmill walking has demonstrated limited effectiveness in improving spatiotemporal gait symmetry (Hornby et al.

2008). On the other hand, amplification of movement errors during gait training has improved inter-limb gait symmetry immediately following a training session (Reisman et al. 2007) and for an extended duration in people post stroke (Reisman et al. 2010; Reisman et al. 2013). Amplifying movement errors may be effective in improving inter-limb symmetry by imposing variations from ‘normal’ movements that are perceptible despite cutaneous and proprioceptive sensory deficits, which might be present in the lower extremity in people post stroke.

In people with sensory deficits, impaired sensory perception results in altered magnitude and timing of muscle activity to coordinate movement (Inglis et al. 1994). For people post stroke, impaired control (i.e., inappropriate timing and scaling of motor responses) during walking may be due, in part, to impaired interpretation of sensory feedback from the paretic limb. Awareness of intra- and inter-limb positions is important for the control of dynamic balance during walking.

Afferent feedback is necessary during sensorimotor tasks, such as walking, to identify movement errors (Wei and Kording 2010). The central nervous system (CNS) is influenced by afferent feedback to modify gait, including adapting to altered walking conditions (Wei and Kording 2009). Adaptation of walking from perceived movement ‘errors’ may be influenced by the ability to appropriately integrate afferent feedback (Wei and Kording 2009) input to spinal and supraspinal centers (Dietz et al. 2002; Frigon and Rossignol 2006). Afferent feedback from the periphery is integrated and compared to predictions of the movement to determine if such feedback can be used to modify future movements (Marigold et al. 2004).

Impairments in sensory feedback may limit the identification of movement errors during walking post stroke. As a result, the modified movement pattern is reinforced and becomes ‘the new normal;’ in that the CNS is unable to identify this movement as asymmetrical. The feedback loop of sensory feedback and motor responses may then lead to limited changes in gait to produce a more symmetrical movement pattern in people post stroke. This cycle may influence rehabilitation as patients have greater difficulty perceiving the movement patterns that are encouraged during locomotor training (Duncan et al. 2007), thereby minimizing the effectiveness of such programs in altering movement patterns to become more symmetrical during walking. Instead, augmented afferent feedback from the lower extremity may provide a large enough deviation from the established gait pattern so that the cerebellum modifies planned motor responses based on this feedback.

Deficits in sensation following stroke may include impaired cutaneous sensation of the plantar surface of the foot (Hillier and Dunsford 2006; Lynch et al. 2007) as well as impaired sense of movement (proprioception) in the paretic limb (Lee et al. 2005; Hillier and Dunsford 2006; Reisman et al. 2007; Tyson et al. 2008). These sensory impairments may contribute to the changes in walking patterns in people post stroke as well as influence walking rehabilitation. Evidence of proprioceptive impairments has been found at the ankle (Lee et al. 2005; Lynch et al. 2007) and the hallux (Hillier and Dunsford 2006) of the more affected limb; however, differences exist in the quality of the assessment. Assessment of movement discrimination deficits at the hallux and ankle (Kim and Choi-Kwon 1996; Lee et al. 2005; Hillier and Dunsford 2006; Lynch et al. 2007; Lin et al. 2012) provides greater information than assessment of movement detection (Tyson et al. 2008). In a study by Tyson et al (2008), impairments in movement discrimination were more prevalent in the upper than the lower extremity, but impairments in movement detection were equally prevalent in the upper and lower extremities (Tyson et al. 2008). A comprehensive sensory assessment, rather than the assessment of a single form of sensory feedback, may be necessary to determine the influence of sensory impairment on walking in people post stroke.

Impairments in lower extremity sensation may be the result of inappropriate processing of feedback in the primary somatosensory cortex, particularly contralateral to the paretic limb following stroke. Appropriate sensory feedback from the lower extremity travels through the dorsal root ganglion to the fasciculus gracilis which then ascends via the dorsal spinocerebellar tract to ventral posterio-lateral nucleus of the thalamus where afferent feedback can then be sent to the postcentral gyrus of the somatosensory cortex. This afferent feedback is then misinterpreted resulting in inappropriate planning of motor responses in the cerebellum. Therefore, the presence of sensory impairments in people post stroke may contribute to reduced gait speed and increased inter-limb asymmetry. Although impairments (strength, coordination, spasticity, tone) have been identified as predictors of gait speed and asymmetry in people post stroke (Hsu et al. 2003), the influence of sensory impairments necessitates further study. Somatosensory impairment in the lower extremity of people post stroke has been identified as a predictor of spatiotemporal asymmetry (Hsu et al. 2003). However, Hsu assessed light touch (cutaneous) and movement detection (proprioception), replicating methods from the lower extremity Fugl-Meyer. The assessment of cutaneous sensation conducted by Hsu (2003) quantified impairment by comparing light touch sensation to the non-paretic limb using a hard and soft item, rather than monofilaments. The proprioceptive assessment conducted by Hsu (2003), based on the ability to identify small (not quantified) movements, also compared the affected to the non-affected limb for scoring. A comprehensive, quantifiable assessment of lower extremity sensation is necessary to identify the role of sensory impairment on gait and asymmetry in people with chronic hemiparesis.

The purpose of this dissertation was to determine the presence of sensory impairments in the lower extremity of chronic people post stroke and the influence of impaired lower extremity sensation on the perception (conscious and unconscious) of spatiotemporal gait asymmetry.

1.1.1 Walking Post Stroke

Although most individuals post-stroke regain the ability to walk (Roger et al. 2012), most (70%) are unable to walk at speeds greater than 0.8 m/s at discharge from rehabilitation (approximately 55 days after admission) (Hill et al. 1997). In addition to walking slowly, people post stroke commonly walk with spatiotemporal inter-limb asymmetry (Patterson et al. 2010), as the paretic limb exhibits prolonged swing time and shorter stance time compared to the non-paretic limb (Kim and Eng 2003; Patterson et al. 2008a). Spatial asymmetry may also exist as a difference in step length between limbs (Patterson et al. 2008a; Patterson et al. 2010). Although locomotor rehabilitation programs have been successful in improving gait speed (Visintin et al. 1998; Silver et al. 2000), improved overground inter-limb symmetry remains elusive (Silver et al. 2000; Patterson et al. 2008a).

Gait training programs have attempted to restore symmetry (Hornby et al. 2008) and gait function (gait speed, functional ambulation category) (Werner et al. 2002; Yagura et al. 2006) through minimization of movement errors. Although the minimization of movement errors is intended to establish a more functional (i.e., faster, reduced assistance or supervision) walking pattern, its effectiveness may be limited by the presence of sensory deficits in people post stroke. Specifically, deficits in lower extremity cutaneous and proprioceptive sensation (Smania et al. 2003; Tyson et al. 2008) may prevent the awareness of subtle changes to paretic limb movements from abnormal established patterns to “normal’ patterns.

Augmented feedback during locomotor training can improve spatiotemporal asymmetry in people post stroke (Reisman et al. 2007; Reisman et al. 2010) by disrupting established movement patterns and promoting exaggerated movements that can be perceived by the lower extremity. The exaggerated movements are integrated into the central nervous system and an altered movement pattern can be developed using feed-forward processes. The use of exaggerated errors to modify walking patterns can establish a more symmetrical walking pattern. For augmented feedback to be effective in modifying spatiotemporal asymmetry in people post stroke, it may be necessary that the magnitude of error augmentation be detectable and beyond the individual's overground spatiotemporal asymmetry. This study will determine the perceptible threshold of inter-limb asymmetry while walking on a split-belt treadmill in relation to overground spatiotemporal asymmetry in people post stroke.

Somatosensory impairment in the lower extremity of people post stroke has been identified as a limiting factor for walking (Hsu et al. 2003) and postural control (Smania et al. 2003). I hypothesized that impaired somatosensory feedback from the lower extremity limits awareness of spatial limb location in relation to the body, disrupting coordination of movements and limiting the perception of when the limb is outside typical patterns of movement. I hypothesize that awareness of abnormal movements of the lower extremity is important for re-establishing a symmetrical movement pattern in people post-stroke. Although gait impairments in people post-stroke have been reported, the influence of lower extremity somatosensory impairment on gait in people with chronic hemiparesis is incompletely understood.

In summary, this study addressed key gaps in the existing literature of sensory impairment in people with chronic hemiparesis due to stroke. Additionally, this study will identify associations among sensory impairment in the lower extremity of people post stroke and perception of spatiotemporal asymmetry during walking. Sensory impairment in the lower extremity of people in the chronic phase post stroke has not been studied comprehensively. Therefore a comprehensive assessment of lower extremity sensation including cutaneous, vibration, and proprioceptive sensory impairments in the paretic limb of people post stroke in the chronic phase of recovery will contribute greatly to identify sensory deficits that persist in people post stroke and the relationship of such sensory deficits to gait. Studies that have investigated lower extremity sensation in people post stroke involve small sample sizes (Hillier and Dunsford 2006) or explore sensation in the acute phase post stroke (Lynch et al. 2007; Tyson et al. 2008). Some studies (Smania et al. 2003; Lynch et al. 2007; Reisman et al. 2007; Tyson et al. 2008; Lin et al. 2012) have included cutaneous or proprioceptive sensation assessment in the lower extremity in people post stroke in some form; such as the assessment of proprioceptive sensation at a specific joint or cutaneous sensation at a single point on the paretic limb only. The influence of sensory impairment on perception of spatiotemporal gait asymmetry will be determined. The success of gait rehabilitation in people post stroke to re-establish a more symmetrical walking pattern may be influenced by the awareness of walking asymmetrically to distinguish variations between established walking patterns developed post stroke and more symmetrical movement patterns during rehabilitation programs.

Specific Aim 1: To identify differences in lower extremity sensation (cutaneous, vibration, and proprioceptive sensation) between paretic and non paretic limbs and to identify associations among measures of lower extremity sensation and overground gait measures (comfortable gait speed, step length asymmetry, stance time asymmetry) in people with chronic stroke.

Hypothesis: The paretic limb of people post stroke will have impaired sensation in the lower extremity compared to the non paretic limb and measures of lower extremity sensation (cutaneous, vibration, and proprioceptive sensation) will be correlated with overground gait speed and spatiotemporal asymmetry ratios (step length, stance time) in people post stroke in that individuals with intact lower extremity sensation will have little overground spatiotemporal asymmetry while individuals with impaired sensation will have greater spatiotemporal asymmetry.

Specific Aim 2: To identify associations among perception (conscious awareness and subconscious detection) of inter-limb asymmetry during treadmill walking and overground walking function (gait speed, step length asymmetry, stance time asymmetry) in people with chronic stroke.

Hypothesis: Perception of inter-limb asymmetry during treadmill walking in people post stroke will be positively correlated with overground walking function (gait speed, step length, stance time asymmetry) in that individuals that perceive small differences in belt speed between treadmill belts will have mild impairments in gait function whereas individuals that perceive only large magnitude differences in speed between treadmill belts will have impaired walking function (slower gait speed overground, increased spatiotemporal asymmetry).

Specific Aim 3: To identify associations among perception (conscious awareness and subconscious detection) of inter-limb asymmetry during treadmill walking and lower extremity sensation (cutaneous, vibratory and proprioceptive sensation) in people with chronic stroke.

Hypothesis: Lower extremity sensation (cutaneous, vibratory, and proprioception) will be negatively correlated with perception of inter-limb asymmetry during treadmill walking in people post stroke in that individuals with intact lower extremity sensation will be capable of perceiving small inter-limb spatiotemporal asymmetry when treadmill walking.

1.2 RESEARCH QUESTIONS

Research Question 1: How does lower extremity sensation differ between the paretic and non-paretic limbs of people with chronic hemiparesis?

Measures of interest:

- Cutaneous sensation of the plantar surface (heel, lateral border of foot, great toe, first metatarsal) of the foot
- Vibration sensation (fibular trochlea, phalanx of hallux, medial femoral condyle)
- Proprioception - movement detection (ankle, knee)

Research Question 2: What is the influence of lower extremity sensory function on perception of inter-limb asymmetry in people post stroke?

Measures of interest:

- Cutaneous sensation of the plantar surface (heel, lateral border of foot, great toe, first metatarsal) of the foot
- Vibration sensation (fibular trochlea, phalanx of hallux, medial femoral condyle)
- Proprioception - movement detection (ankle, knee)
- Stance Time asymmetry ratio
- Step Length asymmetry ratio

1.3 OPERATIONAL DEFINITIONS

<u>Cutaneous Sensation Threshold:</u> Conscious awareness to sensory feedback from receptors sensitive to change in pressure applied to the skin with an accuracy of >80%.

<u>Initial Contact:</u> Point on the vertical ground reaction force curve that exceeds 50 Newtons.

Maximum to threshold: Amplitude of vibration value at which vibration is no longer consciously detected.

Proprioceptive Sensation: Difference in angular position (in degrees) from starting point to the angular position that movement (plantarflexion/dorsiflexion; flexion/extension) at joint (ankle, knee) is consciously perceived.

Stance Time: Duration that one limb is in contact with the ground/treadmill belt during a gait cycle (expressed as a percentage of the gait cycle /100%).

Step Length: Distance between the anteriorly positioned (stepping) foot to the heel of the contralateral (stance) foot at the point of initial contact.

Swing Time: Portion of the gait cycle that the reference limb is not in contact with the ground (normalized to gait cycle).

Vibration Sensory Threshold: Amplitude of vibration that an individual can consciously perceive or can no longer consciously perceive stimulus of oscillation (vibration).

Visual Neglect: Portion of the visual field that is not perceived. For this study visual neglect is defined as fewer than 44 out of 56 stars crossed out on the Star Cancellation Test.

Zero to threshold: Amplitude of vibration value at which vibration is consciously perceived.

1.4 ASSUMPTIONS/LIMITATIONS

The following assumptions and limitations will be made for this study:

- All participants will understand and follow study procedures and will provide their best efforts duing all testing protocols.
- Participants will be able to indicate when they perceive differences in treadmill belt speeds and other sources of sensory feedback.
- Individuals post stroke will be capable of walking on the treadmill at a speed of greater than 0.35 m/s (minimum speed necessary to enact a difference in speed between belts at the 5% difference level).

- This study will apply to people that have experienced an ischemic or hemorrhagic unilateral brain lesion (stroke).
- Individuals post stroke have no cerebellar impairments.

1.5 DELIMITATIONS

The following delimitations will be made for this study:

- All participants will be at least 18 years of age
- Participants will be free of musculoskeletal or neuromuscular injury (in addition to stroke) that impairs walking or standing
- People post stroke will consist of people who have experienced a unilateral or hemorrhagic stroke
- Sensation will be assessed only in the lower extremity (knee, ankle joints, plantar surface of feet)

1.6 INDEPENDENT VARIABLES

The primary independent variable in this study is:

- Difference in speed (m/s) between treadmill belts (expressed as a percent)

Additional independent variables that will be used in this study will be:

- Limb (paretic/non paretic lower extremities)

1.7 DEPENDENT VARIABLES

The following dependent variables will be used in this study:

Spatiotemporal Asymmetry

- Step Length Asymmetry ratio

- Stance Time Asymmetry ratio

Spatiotemporal Gait Characteristics:

- Overground comfortable gait speed
- Overground fast gait speed
- Step Length Asymmetry ratio
- Stance Time Asymmetry ratio

Cutaneous Sensation of plantar surface of the foot:

- Heel
- Lateral border of foot
- Hallux
- Base of first metatarsal head

Vibration Sensation of lower extremity:

- Maximum to threshold
    - Hallux
    - Calcaneous
    - Medial femoral condyle
- Zero to threshold
    - Hallux
    - Calcaneous
    - Medial femoral condyle

Proprioception (movement detection) of lower extremity:

- Knee flexion
- Knee extension
- Ankle dorsiflexion
- Ankle plantarflexion

1.8 SIGNIFICANCE

This study will provide evidence relating the influence of lower extremity sensation on the perception (conscious and subconscious) of inter-limb asymmetry in people post stroke. This study also comprehensively quantifies impairments in lower extremity sensation in people with chronic hemiparesis. Identification of sensory measures associated with spatiotemporal asymmetry may be useful for clinicians to identify key sensory measures in people post stroke.

Identification of sensory measures that are associated with locomotion could then be targeted during rehabilitation to improve acuity in people post stroke.

Additionally, results from this study may influence the use of augmented feedback to modify rehabilitation programs that seek to improve spatiotemporal symmetry. Through identification of the conscious and subconscious thresholds of inter-limb asymmetry perception, future rehabilitation programs will be able to more precisely utilize augmented asymmetry walking for individuals. Currently, walking on a split-belt treadmill with one belt moving at twice the speed of the other has been found to improve overground spatiotemporal asymmetry in one subject post stroke (Reisman et al. 2010). Identification of a threshold of perceivable inter-limb asymmetry lower than a 2:1 ratio while walking on a split-belt treadmill may allow patients to receive the same benefit without having to walk with such a disparity in treadmill belt speeds.

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CHAPTER 2:

Manuscript 1 – Lower extremity sensation is altered in the paretic limb of people with chronic hemiparesis

2.1 INTRODUCTION

Many of the nearly 800,000 people that experience a stroke each year in the United States (Go et al. 2014) have resultant impairments in strength (Andrews and Bohannon 2000; Andrews and Bohannon 2001; Andrews and Bohannon 2003; Moriello et al. 2011), coordination (Tseng and Morton 2010; Raja et al. 2012), or muscle tone (Soyuer and Ozturk 2007). These impairments have been identified as limiting factors for functional tasks, such as walking, in people post stroke (Hsu et al. 2003). In addition to strength or coordination impairments, it is estimated that approximately 60% of individuals acutely (six weeks or less) post stroke have sensory impairments in the paretic upper and lower extremities (Winward et al. 1999; Tyson et al. 2008). In people with chronic hemiparesis, however, the prevalence of sensory impairment in the paretic limb and the resulting differences in sensation between the paretic and non-paretic lower extremities are not well understood and require further examination.

People post stroke have been identified as having impaired cutaneous sensation of the plantar surface of the paretic foot acutely (Lynch et al. 2007) and chronically (n=3) (Hillier and Dunsford 2006) as well as an impaired sense of movement (proprioception) in the paretic limb (Lee et al. 2005; Hillier and Dunsford 2006; Reisman et al. 2007; Tyson et al. 2008). These studies were limited, however because assessment of cutaneous sensation of the paretic foot has focused on people in the acute phase of stroke rehabilitation (Lynch et al. 2007; Tyson et al.

2008) or used few testing sites (Hillier and Dunsford 2006), neglecting other areas of the foot that provide feedback for dynamic balance tasks such as walking. Evidence of proprioceptive impairments has been found at the ankle (Lee et al. 2005; Lynch et al. 2007) and the hallux (Hillier and Dunsford 2006) of the paretic limb; however, differences exist in the quality of the assessment. Movement detection, commonly conducted with the investigator manipulating the segment to be tested, may provide movement related cutaneous cues or limited standardization of the speed of movement during testing. In addition to impaired movement detection, movement discrimination deficits have also been identified at the hallux and ankle (Kim and Choi-Kwon 1996; Lee et al. 2005; Hillier and Dunsford 2006; Lynch et al. 2007; Lin et al. 2012) of people post stroke, providing greater information than assessment of movement detection alone (Tyson et al. 2008).

If present, sensory impairments in people post stroke may contribute to abnormal walking patterns, as impaired sensation of the paretic limb has previously been identified as a predictor of spatiotemporal asymmetry (Hsu et al. 2003). Sensory feedback from the lower extremity is necessary to identify movement errors during walking (Dietz et al. 2002). Following stroke, sensory impairments may result in inaccurate planning of movements and/or motor responses (Wutzke et al. 2013). If sensory impairment in people with chronic hemiparesis is common, rehabilitation programs may benefit from the inclusion of sensory retraining to improve identification of movement errors. Therefore, a comprehensive, quantifiable assessment of lower extremity sensation is necessary to identify sensory impairment and determine the influence of sensory impairment on gait speed and spatiotemporal asymmetry in people with chronic stroke.

The purpose of this study was to determine differences in sensation between the paretic and non-paretic lower extremities of people with chronic hemiparesis. A secondary purpose was to determine associations among measures of lower extremity sensation and overground walking measures. We hypothesized that the paretic limb of people with chronic hemiparesis would have impairments in sensation compared to the non-paretic limb. Additionally, based on previous work (Hsu et al. 2003)(Wutzke, Faldowksi, Mercer, in process), it was hypothesized that impairments in lower extremity sensation would be associated with slower walking speed and greater spatiotemporal asymmetry in people with chronic hemiparesis.

2.2 METHODS

Thirty people post stroke ($\bar{x}$ age: 58.60±13.36 years, $\bar{x}$ height: 170.31±10.34 cm, $\bar{x}$ weight: 82.70±17.77 kg, 17M/13F, 18 left limb paretic) were recruited to participate in the study. All subjects read and signed an IRB approved informed consent document. Confirmation of ischemic or hemorrhagic stroke was provided by a physician prior to participation. Participants were at least six months post stroke and used an assistive device or lower extremity bracing (i.e. ankle/foot orthosis) for walking as needed. Exclusion criteria included: 1) inability to walk without physical assistance, 2) history of lower extremity joint surgery (e.g., total joint arthroplasty) or disease that might reduce sensation in the lower extremity (e.g. diabetes), 3) vision impairments not corrected by lenses, visual neglect, or vestibular deficits, and 4) inability to follow three step commands. Prior to testing, motor coordination was assessed using the lower extremity portion of the Fugl-Meyer (Gladstone et al. 2002). Subjects were screened for unilateral visual neglect (star cancellation test), vision impairments (self-report of visual impairments), and vestibular impairments (self-report of vestibular deficits).

Table 1. Individual subject demographic data of study participants.

Subject	Paretic Limb	Gender	Age (years)	Months Post Stroke	AFO	Cane	Fugl-Meyer
D1	L	F	45	50	yes	no	27
D2	L	M	69	210	yes	yes	26
D3	R	F	46	66	no	no	30
D4	L	M	38	56	no	no	25
D5	L	M	79	41	no	no	28
D6	L	M	67	83	no	no	25
D7	L	M	74	28	yes	no	20
D8	L	M	66	470	no	no	27
D9	R	F	48	8	no	no	28
D10	R	M	55	32	yes	yes	17
D11	L	F	43	118	no	no	21
D12	L	M	29	40	yes	yes	26
D13	L	F	63	56	no	no	25
D14	R	M	48	15	yes	no	19
D15	R	F	55	53	no	no	29
D16	L	F	61	125	yes	no	17
D17	R	F	64	34	no	yes	17
D18	R	M	57	99	no	no	26
D19	R	F	47	50	no	no	19
D20	R	M	59	107	no	no	23
D21	L	F	61	45	yes	yes	23
D22	L	F	47	95	yes	yes	15
D23	R	M	59	77	no	no	27
D24	R	M	70	148	no	no	30
D25	L	F	58	379	no	no	26
D26	L	M	75	63	yes	yes	19
D27	L	F	46	257	no	no	29
D28	R	M	81	142	no	no	27
D29	L	M	86	67	no	no	27
D30	L	M	62	80	no	no	30
	Mean	17M	58.60	103.13	10AFO	7Cane	24.27
	St. Dev	13F	13.36	103.75			4.48

2.2.1 DATA COLLECTION

Overground walking measures were calculated from three walking trials at a self-selected speed over a 14 foot GaitRite mat (CIR Systems Inc, Havertown, PA). Sensory testing included cutaneous (Hillier and Dunsford 2006; Lynch et al. 2007; Tyson et al. 2008), vibration (Gin et al. 2011), and proprioceptive sensation (Carey et al. 1996; Lund et al. 2008; Tyson et al. 2008; Goble 2010) of both lower extremities. Subjects performed all sensory tests with eyes closed.

Cutaneous sensation was assessed at four sites on the plantar surface of the foot (*heel, great toe, lateral border of the foot* (1/2 the distance from the tip of the 5th toe to the heel), and *base of 1st metatarsal*) with a set of five Semmes Weinstein monofilaments (2.83, 3.61, 4.31, 4.56 and 6.65g). Subjects were in a seated position, knees flexed ~90 degrees and feet off the ground to access the plantar surface of the foot. The threshold of cutaneous sensation at each site was identified as the minimum gauge of monofilament detected with an accuracy of 80% or greater (Feng, 2009). A minimum of 15 trials were conducted at each site beginning with the mid-point monofilament (4.31g). Subjects who correctly identified the monofilament in contact at the test site were then tested with a smaller gauge monofilament (2.83g) whereas subjects who did not detect the 4.31g monofilament were then tested with the 6.65g monofilament. Each site was then tested with the next larger/finer monofilament, dependent upon whether the subject correctly or incorrectly detected the monofilament. Additionally, 'catch' trials were included, when no contact was made between the monofilament and surface of the skin, at a rate of approximately 1 in 5 (Feng, 2009).

Vibration sensation was assessed with a bio-thesiometer (Bio-Medical Instrument Company, Newbury, OH), at the lateral calcaneous, distal phalanx of the hallux, and the medial femoral condyle. At each site, the threshold of vibration sensation was assessed using two techniques. *Zero to detection threshold* testing was conducted by incrementally (approximately one unit per second) increasing the amplitude of vibration from zero until the subject identified the site as vibrating with a verbal response. The second technique, *maximum to threshold,* was conducted with the bio-thesiometer at the maximum amplitude and then slowly reduced in frequency until the subject identified the vibration as absent. Each procedure was replicated five times at each site.

Proprioceptive sensation was assessed at the ankles and knees using a movement detection task, performed while seated on a Cybex Norm (CSMi, Stoughton, MA). At each site, the passive range of motion for the joint was determined. To assess movement detection at the ankle, the hip and knee were flexed approximately 75 and 90 degrees respectively and the motor's axis of rotation was aligned with the lateral malleolus. To test the knee, subjects were seated with the hips flexed approximately 75 degrees and the motor's axis of rotation aligned with the lateral femoral condyle (van der Esch et al. 2007). Trials consisted of passively moving the segment to the respective starting position (mid-point of the range of motion for the ankle, 30 degrees of flexion for the knee (Hurkmans et al. 2007; van der Esch et al. 2007)) and then passively rotating the joint at one degree per second until the participant identified movement at the joint. Three flexion/dorsiflexion trials and three extension/plantarflexion trials were conducted at each joint with the angular change in position between the starting position and the angle that the participant identified movement of the segment recorded.

2.2.2 DATA MANAGEMENT

The minimum threshold of cutaneous sensation was converted to a rank scale (e.g., 1 to 6) such that the monofilament that produced the least force (2.83 grams) was ranked 1 and each subsequent monofilament increased in ranked value 3.61 (2), 4.31 (3), 4.56 (4), 6.65 (5). A score of 6 was provided if the participant was unable to identify when the 6.65 was in contact with the skin at a specific location.

The average threshold of vibratory sensation for the zero to threshold and maximum to threshold trials was calculated for each of the three locations on the paretic and non paretic legs for each participant respectively. If a participant could not identify vibration at the machine's maximum value (i.e., 50) during a trial, a value of 51 was recorded.

Proprioceptive scores were calculated as angular deviations for each trial of passive flexion/dorsiflexion and extension/plantarflexion at both the paretic and non-paretic knee/ankle. An average angular deviation was calculated for each joint direction for each limb (paretic and non-paretic).

Self-selected overground walking speed, step length, and stance time asymmetry ratios were calculated as the average of the three walking trials. Step length and stance time were calculated for each limb (paretic and non paretic) with the larger value divided by the smaller value to determine the asymmetry ratio (Lewek and Randall 2011).

2.2.3 DATA ANALYSIS

Comparisons between the paretic and non paretic feet for each site of each sensory measure were conducted using a Wilcoxon Signed Rank test with an alpha level of 0.05.

Multiple comparisons were controlled for by employing the Benjamini-Hochberg False Discovery Rate (Benjamini and Hochberg 1995). Impairment at the paretic and non paretic limb for each test was determined by comparison to mean values in existing literature of similarly performed tests in unimpaired, similarly aged adults. Cutaneous sensation data were compared to healthy control data from studies that used monofilaments to determine a threshold of perception at each of the sites tested in the present study (Jeng et al. 2000). Vibratory sensation at each site was compared to zero to threshold values from studies that included participants with no sensory impairment (Shakoor et al. 2008). Proprioception impairment in people post stroke was compared qualitatively to unimpaired similarly aged adults performing movement detection tasks at similar speeds (0.5 to 1 degree per second movement) and similar starting positions (Xu et al. 2004; van der Esch et al. 2007; Lund et al. 2008). To determine associations among lower extremity sensation and spatiotemporal walking characteristics, Spearman rank correlations were conducted with an alpha level of 0.05.

2.3 RESULTS

On the paretic limb 26/30 participants displayed impaired cutaneous sensation (score of > 4.31, (Kokmen et al. 1977; Jeng et al. 2000; Collins et al. 2010)) at one or more of the four sites tested in comparison with 18/30 of participants displaying a cutaneous score >4.31 at one or more sites on the non paretic foot . Sensation differed between the paretic and non paretic feet at each of the four sites tested (Table 2). On the plantar surface of the great toe, the average ranked cutaneous score was 3.73±1.23 on the paretic foot compared to the average score on the non paretic foot (2.87±0.73; p=0.001). At the lateral border of paretic foot the average ranked cutaneous score was 3.50±0.82 compared to 3.03±0.61 (p=0.007) at the non paretic lateral border of the foot. The plantar surface of the heel on the paretic foot had an average ranked cutaneous score 0.57 greater than the non paretic foot (4.29±0.81 paretic, 3.73±0.87 non paretic; p=0.008). The base of the first metatarsal head on the paretic foot had an average ranked cutaneous score of 3.54±1.00 on the paretic limb compared to 2.97±0.76 on the non paretic foot (p=0.005).

Table 2: Ranked scores of cutaneous sensation of paretic and non paretic plantar surface of foot (mean + standard deviation) with p values.

	Paretic	Non Paretic	P Value
Great Toe	3.73±1.23	2.87±0.73	p=0.001
Lateral Border	3.50±0.84	3.03±0.61	p=0.007
Heel	4.29±0.81	3.73±0.87	p=0.008
Base 1st Metatarsal	3.54±1.00	2.97±0.76	p=0.005

Vibration sensation also differed between the paretic and non paretic limbs in people with chronic hemiparesis (Table 3). At the paretic heel, the average Zero to Threshold score was 27.35±15.51 while the average Maximum to Threshold score was 24.32±10.15. At the heel of the non paretic limb, the average Zero to Threshold score was 20.34±13.34 (p<0.001) and Maximum to Threshold score was 21.12±10.01 (p=0.008) respectively. The Zero to Threshold scores were 24.59±14.40 and 20.31±14.49 at the great toe for the paretic and non paretic limbs respectively (p=0.021). Compared to existing literature of unimpaired adults of similar age (6.40±3.30) (Shakoor et al. 2008), 29/30 participants had impaired zero to threshold vibratory sensation in the paretic limb at the great toe and 28/30 at the non paretic great toe (Shakoor et al. 2008). Maximum to Threshold scores at the great toe did not significantly differ between paretic and non paretic limbs (24.93±9.44 and 20.31±14.49, p=0.544). The Zero to Threshold score at the medial femoral condyle was significantly greater on the paretic limb (32.30±12.68) than the non paretic limb (23.92±10.42, p<0.001), however no difference was found at the medial femoral condyle for Maximum to Threshold (27.98±9.57 paretic, 24.97±10.74 non paretic; p=0.355). 28/30 were identified as displaying impaired sensation at the medial femoral condyle at the paretic limb compared to existing literature (15.90±7.0) (Shakoor et al. 2008). At the non paretic limb, 25 of 30 participants were identified as having impaired vibratory sensation at the medial femoral condyle using the zero to threshold technique (Shakoor et al. 2008).

Table 3: Average vibratory sensation at heel, great toe, and medial femoral condyle (mean + standard deviation, p values) of paretic and non paretic feet of people with chronic hemiparesis.

Site	Technique	Paretic	Non Paretic	P Value
Heel	Zero to Threshold	27.35+15.51	20.34+13.34	p<0.001
	Max to Threshold	24.32+10.15	21.12+10.01	p=0.008
Great Toe	Zero to Threshold	24.59+14.40	20.31+14.49	p=0.021
	Max to Threshold	24.93+9.44	23.92+10.42	p=0.544
Medial Femoral Condyle	Zero to Threshold	32.30+12.68	23.92+10.42	p<0.001
	Max to Threshold	27.98+9.57	24.97+10.74	p=0.355

Movement detection at the ankle and knee differed between the paretic and non paretic limbs of people with chronic hemiparesis (Table 4). A greater change from the start position was necessary for participants to identify movement of the paretic compared to the non paretic ankle during plantarflexion (4.80±6.55° paretic, 1.98±1.71 non paretic, p=0.009) and dorsiflexion (3.57±4.76 paretic, 1.98±2.15 non paretic, p=0.035). 17/30 participants were identified as having impaired movement detection at the paretic ankle (plantar or dorsiflexion) while 8/30 were found to have impaired sensation at the non paretic ankle compared to existing literature (Xu et al. 2004). Detection of knee flexion required greater flexion in the paretic limb (6.79±11.11) than the non paretic limb (1.70±1.38, p<0.001), as well as greater extension excursion at the paretic knee to identify movement compared to the non paretic knee (5.23±8.03 paretic, 1.75±1.14 non paretic; p=0.043). Previous studies have identified movement detection of flexion and extension at the knee in unimpaired, similarly aged adults to be 1.08-1.57 degrees (Hurkmans et al. 2007; Lund et al. 2008). With these values as a baseline, 21/30 participants demonstrated impairments in knee proprioception in the paretic limb and 15/30 with impaired sensation on the non paretic limb.

Table 4: Average change in position (in degrees) at ankle and knee of paretic and non paretic limbs (mean + standard deviation, p values).

	Ankle		Knee	
	Plantarflexion	Dorsiflexion	Extension	Flexion
Paretic	4.80±6.55	3.57+4.76	5.23±8.03	6.79±11.11
Non Paretic	1.98±1.71	1.98±2.15	1.75±1.14	1.70±1.38
P Value	p=0.009	p=0.035	p=0.043	p<0.001

The comfortable overground walking speed was 0.79±0.21 m/s (range 0.36-1.16 m/s) with an average step length asymmetry of 1.13±0.13 (range 1.01-1.37) and average stance time asymmetry of 1.14±0.11 (range 1.01-1.37). Of the 30 participants, ten wore an ankle/foot orthosis (AFO) during walking trials and seven used a cane (single point or quad point) for walking. The average Fugl-Meyer lower extremity motor score was 24.27±4.48.

Significant correlations were identified among overground gait measures and lower extremity sensation. Comfortable walking speed was associated with cutaneous sensation of the lateral border on the non paretic foot ($r_s = 0.390$, p=0.033). Stance time asymmetry was correlated with the threshold of vibration on both the paretic and non paretic limbs. On the paretic limb, stance time asymmetry ratio was associated with the Zero to Threshold and Maximum to Threshold vibration scores at the medial femoral condyle ($r_s = -0.423$, p=0.020, $r_s = -0.380$, p=0.038 respectively). We observed significant associations between stance time asymmetry and the vibration sensation of the non-paretic hallux, calcaneous, and medial femoral condyle. At the hallux of the non paretic limb, stance time asymmetry was correlated with both the Zero to Threshold and Maximum to Threshold vibration scores (r_s = -0.441, p=0.015, r_s = -0.365, p=0.047 respectively). At the non paretic calcaneous, the Zero to Threshold vibration score was correlated with stance time asymmetry ratio (r_s = -0.449, p=0.013) while Zero to Threshold vibration score at the non paretic medial femoral condyle was correlated with stance time asymmetry ratio (r_s = -0.484, p=0.007).

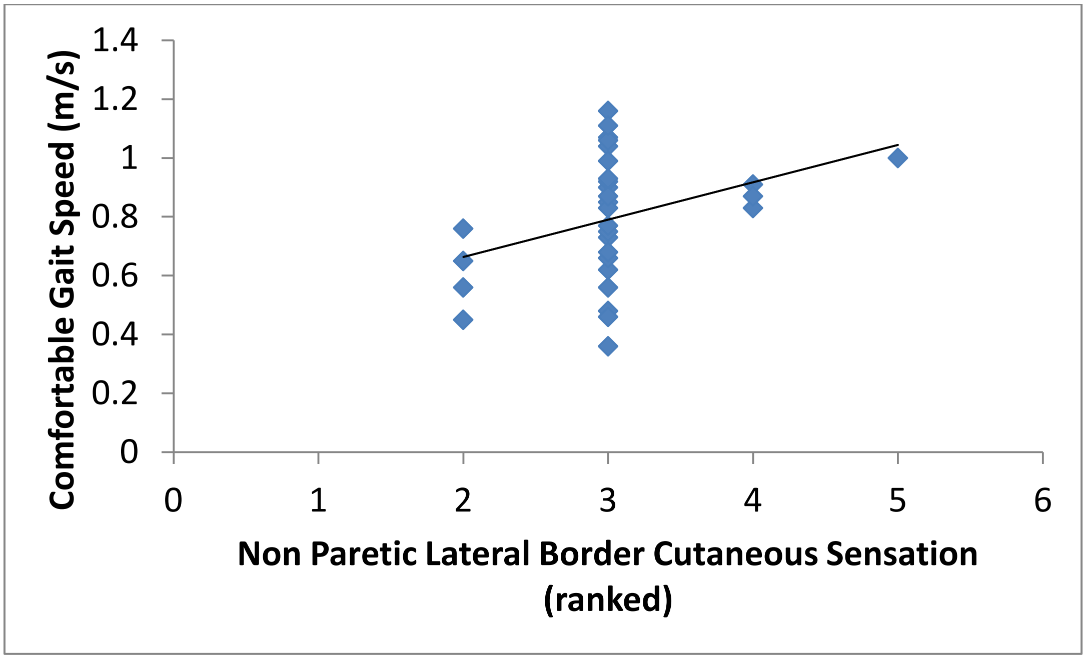

Figure 1 Correlation of cutaneous sensation of the non paretic lateral border (ranked) and comfortable overground gait speed (m/s).

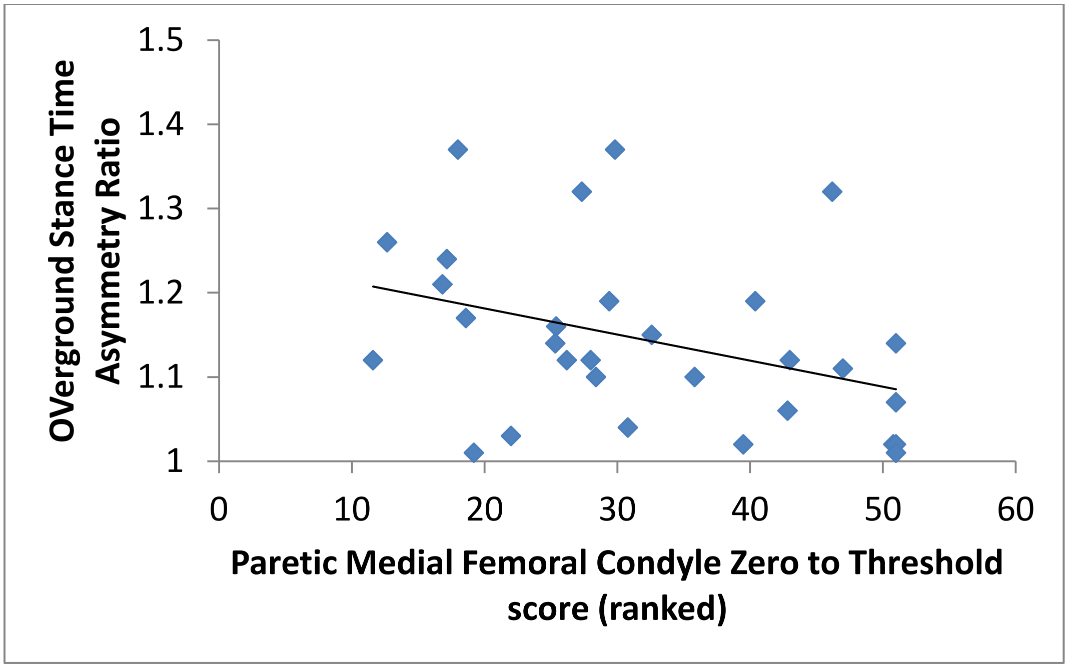

Figure 2 Correlation of vibration sensation of the paretic medial femoral condyle and overground stance time asymmetry ratio.

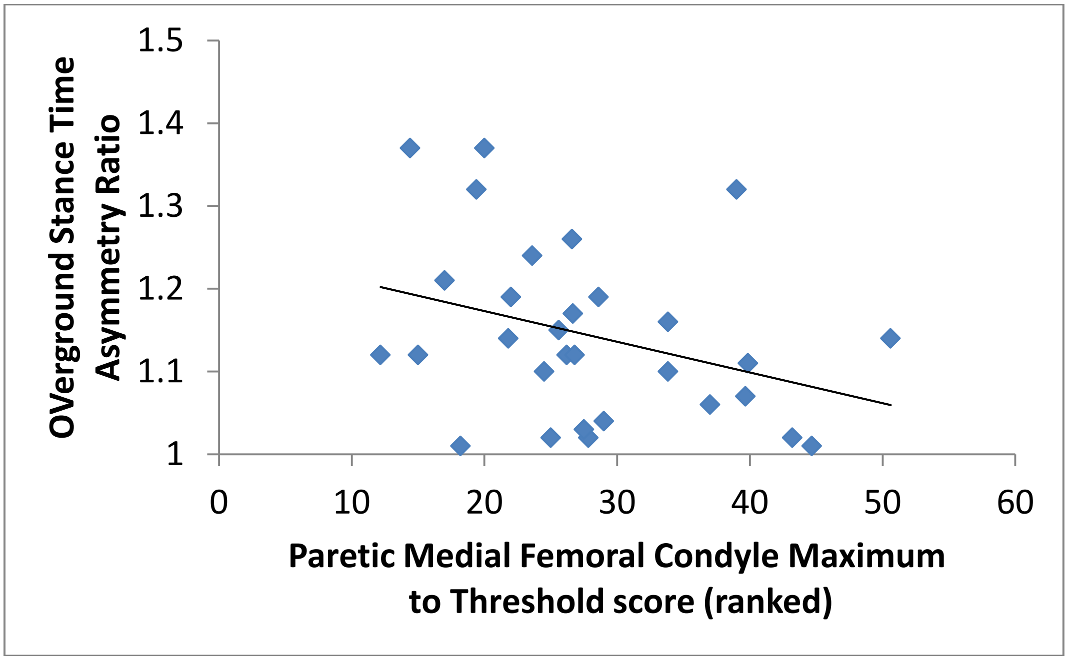

Figure 3. Correlation of vibration sensation of paretic medial femoral condyle and overground stance time asymmetry ratio.

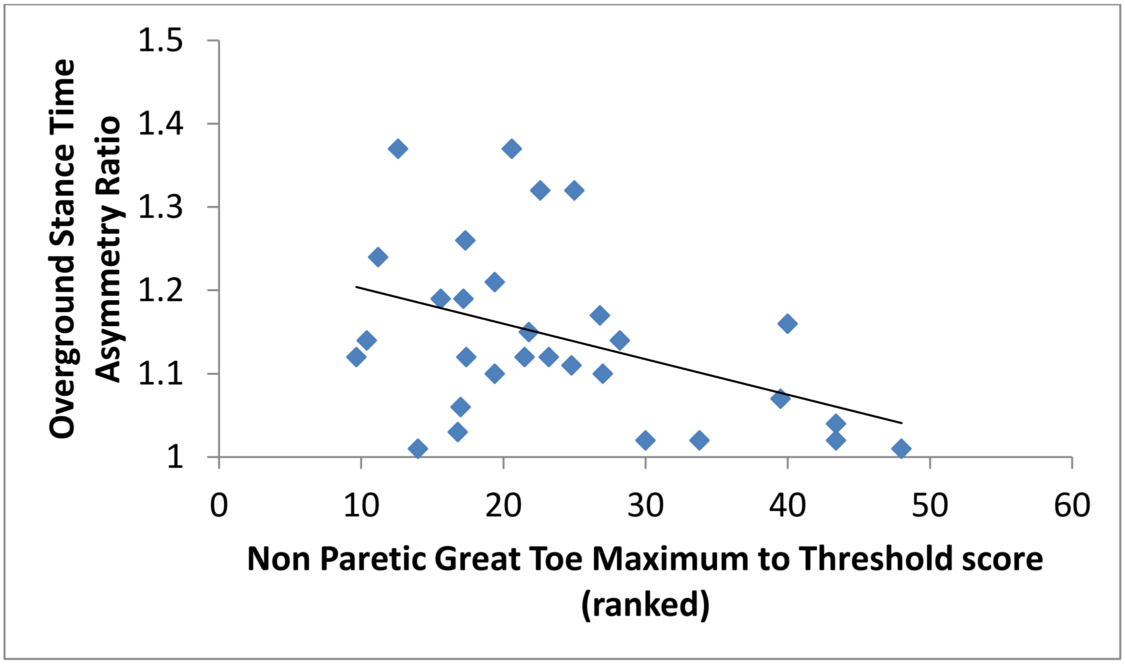

Figure 4. Correlation of vibration sensation of paretic hallux and overground stance time asymmetry ratio.

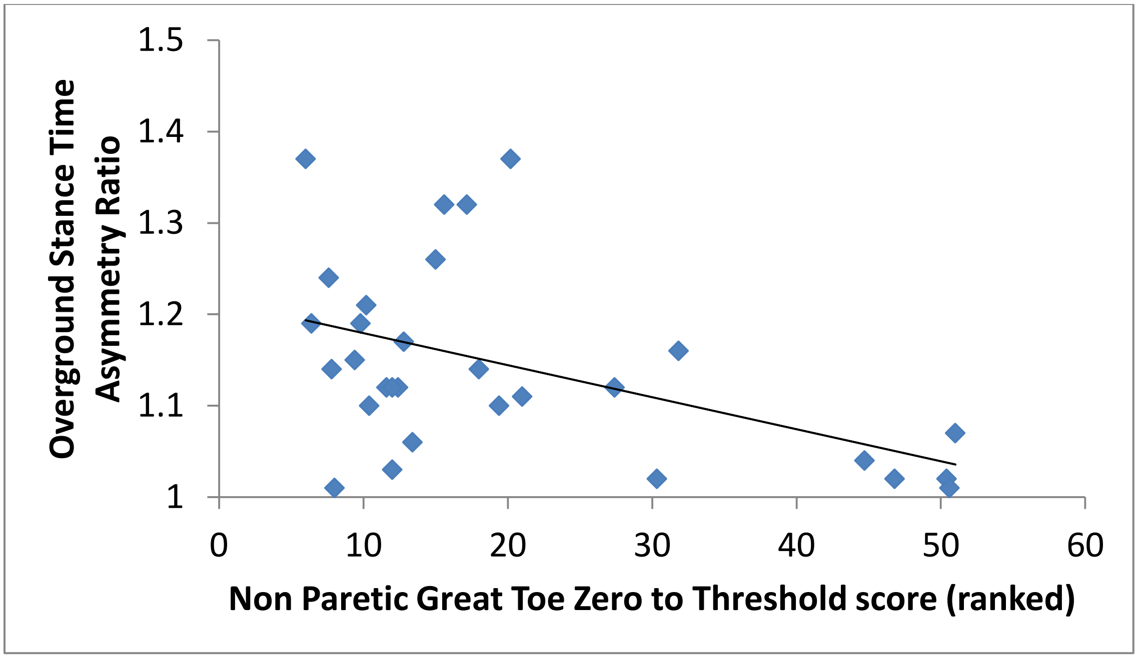

Figure 5. Correlation of vibration sensation of non paretic hallux and overground stance time asymmetry ratio.

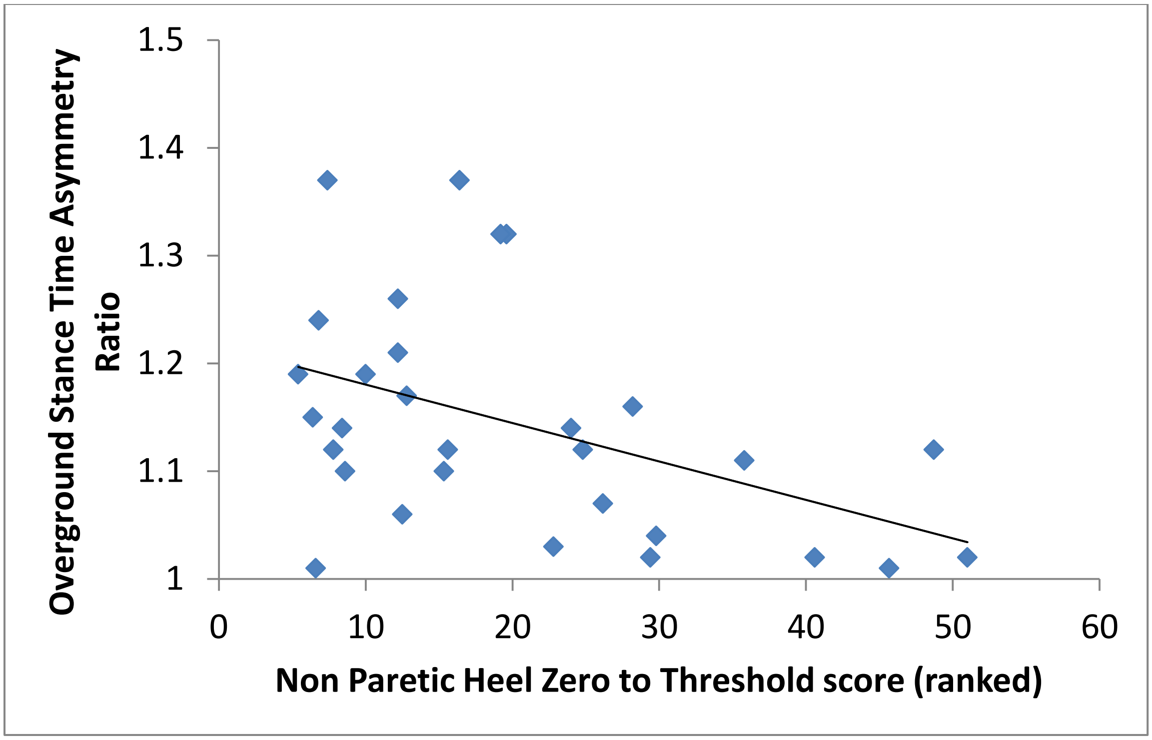

Figure 6. Correlation of vibration sensation of non paretic heel and overground stance time asymmetry ratio.

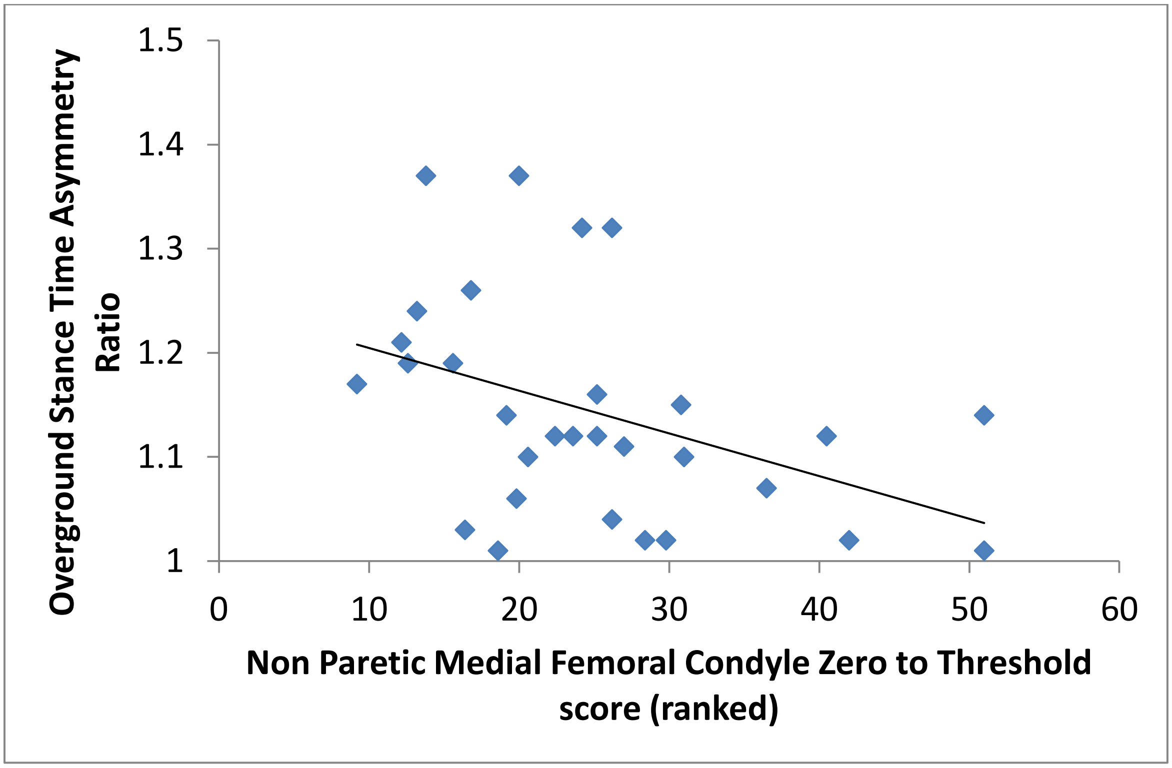

Figure 7. Correlation of vibration sensation at non paretic medial femoral condyle and overground stance time asymmetry ratio.

2.4 DISCUSSION

The purpose of this study was to determine differences in lower extremity sensation between the paretic and non-paretic limbs of people with chronic hemiparesis and to identify associations with spatiotemporal characteristics of overground walking. We hypothesized that sensation in the paretic limb would be impaired compared to the non-paretic limb of people post stroke and that impairments in lower extremity sensation would be correlated with increased spatiotemporal gait asymmetry.

Our results indicate cutaneous, vibration, and proprioceptive sensation is diminished in the paretic limb compared to the non-paretic limb of people post stroke. Tyson also identified sensory deficits in the lower extremity in people in the acute phase of rehabilitation (Tyson et al. 2008; Tyson et al. 2013). Tyson et al found impairments in light touch and movement detection at the plantar surface of the foot and shank (Tyson et al. 2008). Our results suggest that a similar percentage of people post stroke in the chronic phase of hemiparesis have sensory impairments in the lower extremity compared to people in the acute phase of rehabilitation (62.75%).

Studies indicating sensory impairments in the lower extremity of people with chronic hemiparesis are limited, however studies that have investigated lower extremity sensation in people post stroke have also identified impairments. Movement detection was identified as impaired at the ankle in the lower extremity of people post stroke in a pilot study completed by Hillier and Dunsford that explored the effectiveness of sensory retraining in people at least two years post stroke (Hillier and Dunsford 2006). Lee found impairments in detection of movement at the ankle in a study of eleven people with chronic hemiparesis (Lee et al. 2005). The current study also found impaired movement detection in people post stroke at the ankle when tested at a movement speed of one degree per second. In the Lee study, six of the eleven participants had significant impairment of sensation in the paretic limb (Lee et al. 2005). In the current study, we identified 17 of 30 participants that displayed impairment in movement detection at the paretic ankle.

To determine the prevalence and persistence of lower extremity sensory impairment in people post stroke, longitudinal cohort studies are necessary. Sensory assessment of people post stroke should be initiated in the acute phase of stroke rehabilitation (similarly to (Tyson et al. 2008)) and then assessed periodically (i.e. semi-annually) to identify the prevalence of lower extremity sensory impairments in people post stroke and the potential recovery of sensation as they progress to the chronic phase of hemiparesis. Such studies would provide valuable information regarding sensory changes that may occur as people progress through to the chronic phase of hemiparesis.

Sensory impairment in people post stroke may influence the ability to appropriately adapt walking patterns to changes in conditions (i.e. change in surface) or demand (increase/decrease in walking speed). To identify movement errors and produce coordinated movements, sensory feedback from the periphery provides information to the central nervous system regarding the position, movement information, and interaction with the environment (i.e. walking surface). The central nervous system uses afferent feedback to modify movement patterns, including adaptation to altered walking conditions (Wei and Kording 2009). Misinterpreted sensory feedback may result in inappropriate neuromuscular responses to the demands of the environment to make predictive (feed-forward) adjustments (Reisman et al. 2005; Choi et al. 2009). Likewise, feedback from the extremities is integrated and compared to predictions of the movement to determine if such feedback can be used to modify future movements (Marigold et al. 2004). In the context of people post stroke, afferent feedback received from the lower extremity remains unchanged as a result of the stroke, but instead the interpretation of sensory information and resultant motor response may be altered following stroke. As a result of this inappropriate interpretation of sensory feedback in the central nervous system, it may be necessary to augment movement errors to provide a magnitude of sensory feedback that can be perceived as different from typical movements in the cerebellum.

Interestingly, lower extremity sensory impairments were negatively correlated with walking function (comfortable gait speed, step length asymmetry, stance time asymmetry). This suggests that lower extremity sensation as assessed in the present study may not be necessary for people in the chronic phase of rehabilitation to walk. Although lower extremity sensation has been identified as necessary for fine motor control such as stepping over an obstacle which has been identified in cats (Rossignol et al. 1996), people post stroke may utilize other sensory cues, such as afferent information at the hip (Dietz et al. 2002) to maintain walking function.

There is evidence that suggests lower extremity sensation is not positively correlated with walking function. Perry et al (1995) examined proprioceptive sensation at the hallux, ankle, knee and hip of the paretic lower limb in people post stroke and found no association with walking function (Perry et al. 1995). Reisman et al, reported 11 of 13 subjects had impaired cutaneous sensation (detection threshold greater than 3.61 grams) at the hallux, however no significant association between sensory impairment (cutaneous or proprioceptive sensation) and adaptive ability was found (Reisman et al. 2007). Results of the Reisman et al study may have been influenced by the single location on the paretic foot (Reisman et al. 2007). Although cutaneous input from the great toe provides feedback about when the foot transitions to swing phase, input from other sites, such as the heel and lateral border of the foot, may also be critical during locomotion to maintain dynamic balance. Sensory input from the heel typically provides feedback regarding initial contact with the ground while input from the lateral border of the foot provides information regarding the transition from braking to propulsion. Without sensory feedback from these sites, walking may be slower and more cautious (Eils et al. 2004).

Based on the result of the present study, lower extremity sensation deficits are common in people with chronic hemiparesis. Assessment of lower extremity sensation should include both the paretic and non paretic limbs as impairments were identified in both limbs when compared to the mean value of similarly aged adults. Cutaneous sensation at multiple sites is necessary as previous studies that assessed sensation at a single site did not identify associations with walking function in people post stroke and most participants in the present study demonstrated cutaneous impairment at one or more sites. The results of this study suggest that nearly all subjects demonstrated impaired vibratory sensation. Further studies investigating vibratory sensation in people post stroke are necessary to determine the importance of vibratory sensation in people post stroke. Vibration sensation of people post stroke was more similar to adults with knee osteoarthritis than unimpaired adults (see results section). The majority of people post stroke (18 of 30) required greater vibratory stimuli than people with osteoarthritis (>15.0) to perceive vibration at the great toe at the paretic limb (Shakoor et al. 2008). At the medial femoral condyle, people with osteoarthritis had a mean vibratory threshold of 25.8 (Shakoor et al. 2008). In the present study 21 of 30 subjects post stroke required greater vibratory amplitude to perceive the stimuli in the paretic limb.

Limitations of the study included testing of individuals post stroke with minor to moderate functional impairment as determined by self-selected overground walking speed.

Individuals with severe functional impairment may have more significant sensory impairments than the individuals tested in the present study. Additionally, the testing position for ankle proprioception has little contribution from the gastrocnemius. The position employed was the manufacturer's recommended position for evaluation of ankle plantarflexion/dorsiflexion, however this may have influenced subjects' ability to detect motion at the ankle.

2.5 CONCLUSIONS

The current study is the first to identify and quantify multiple sources of sensory impairment in the paretic limb of people with chronic hemiparesis. Differences between the paretic and non paretic limbs were found in each of cutaneous, vibration, and proprioceptive sensations. Although differences in sensation were found between limbs, sensation in the lower extremity appears to be unrelated to overground walking characteristics in people post stroke as only cutaneous sensation of the non paretic foot at the lateral border was associated with walking at a self-selected speed. This suggests that sensory retraining in the lower extremity following stroke may be of limited benefit to improve walking function in people post stroke. Further study is necessary to determine the association between sensory impairment and an individual's ability to identify the presence of walking asymmetry in people post stroke.

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CHAPTER 3:

Manuscript 2 – Perception of asymmetry is associated with overground spatiotemporal asymmetry in people post stroke

3.1 INTRODUCTION

People with hemiparesis commonly experience impairments in strength (Andrews and Bohannon 2000; Andrews and Bohannon 2001; Andrews and Bohannon 2003; Moriello et al. 2011), coordination (Tseng and Morton 2010; Raja et al. 2012), and/or sensation (Bohannon 2003; Lynch et al. 2007; Tyson et al. 2008) in the paretic limb, often resulting in greater dependence on the non paretic limb (Patterson et al. 2010; Hendrickson et al. 2014). This asymmetry between limbs of people post stroke may have functional consequences including reduced walking speed (Allen et al. 2011; Hendrickson et al. 2014; Patterson et al. 2014) or asymmetry when walking (Patterson et al. 2010; Allen et al. 2011; Patterson et al. 2014), potentially increasing the risk of a fall (Tutuarima et al. 1997; Weerdesteyn et al. 2008; Wagner et al. 2009; Tsur and Segal 2010). Asymmetrical walking patterns that are established acutely, when impairments in strength and coordination are greatest, often persist beyond the acute phase of rehabilitation. In fact, despite improvements in walking speed, balance, and functional mobility following a rehabilitation program, spatiotemporal asymmetry remains in people post stroke (Patterson et al. 2014). People post stroke commonly exhibit spatial (step length) or temporal (stance time) asymmetry when walking at a self-selected speed (Patterson et al. 2010; Patterson et al. 2014). It has been estimated that as many as 49% of people post stroke walk with a spatial asymmetry (Patterson et al. 2008a; Patterson et al. 2010) whereas as many as 60% of people post stroke walk with temporal asymmetry (Patterson et al. 2008a; Patterson et al. 2010).

Reisman has demonstrated that people post stroke with spatiotemporal asymmetry are capable of producing a symmetrical walking pattern following treadmill walking that augments spatiotemporal asymmetry (Reisman et al. 2009; Reisman et al. 2010; Reisman et al. 2013). This suggests that people post stroke have the neuromuscular capability of producing symmetrical walking patterns but select an asymmetrical walking pattern. Additionally it has been found that despite walking on a split belt treadmill that either augmented or minimized spatiotemporal asymmetry, people post stroke returned to their baseline asymmetry as they adapted to walking with each limb at a different speed (Malone and Bastian 2014). This plateau effect may be because people post stroke perceive their asymmetrical walking pattern as normal, and are unable to distinguish between their established ‘normal’ walking pattern and walking patterns that are more symmetrical. Therefore, for people post stroke, the perception of walking patterns that differ from their ‘normal’ established walking pattern may be crucial to the development of a more symmetrical walking pattern and increasing our understanding of why people post stroke select an asymmetrical walking pattern.

Impaired perception has previously been identified in the distribution of weight during standing (Schaefer and Bohannon 1990; Mansfield et al. 2011) and may be related to walking asymmetry in people post stroke (Hendrickson et al. 2014). The perception of walking asymmetry may be associated with the magnitude of spatiotemporal asymmetry in established walking patterns in people post stroke. Individuals with large magnitudes of spatiotemporal asymmetry may perceive this pattern as normal and therefore require a magnitude of asymmetry that exceeds their typical overground asymmetry to recognize asymmetry. It is unclear however, if magnitude of spatiotemporal asymmetry influences the ability to perceive changes in walking patterns in people post stroke.

The purpose of this study was to determine the threshold of asymmetry perception (conscious and subconscious) during split-belt treadmill walking in people with chronic hemiparesis. A secondary purpose of this study was to determine associations among overground walking function (step length and stance time asymmetry ratios, walking speed) and the perception (conscious and subconscious) of walking asymmetry while walking on a split-belt treadmill in people with chronic hemiparesis. We hypothesized the threshold of conscious perception would exceed overground spatiotemporal asymmetry in people with chronic hemiparesis. It was also hypothesized that large overground spatiotemporal asymmetry ratios and reduced walking speed would be associated with impaired perception of asymmetrical walking while walking on a split-belt treadmill.

3.2 METHODS

Thirty people post stroke ($\bar{x}$ age: 58.60±13.36 years, $\bar{x}$ height: 170.31±10.34 cm, $\bar{x}$ weight: 82.70±17.77 kg, 17M/13F, 18 right limb paretic, 12 left limb paretic) were recruited to participate in the study. All subjects read and signed an IRB approved consent document. Inclusion criteria included ischemic or hemorrhagic unilateral brain lesion as diagnosed by a physician. Participants were at least six months post stroke and used an assistive device or lower extremity bracing (i.e. ankle/foot orthosis) for walking when necessary. Exclusion criteria included: 1) cerebellar lesion 2) inability to walk without physical assistance, 3) lower extremity joint replacement or injury in the lower extremity in the past six months, 4) self report of vision impairments not corrected by lenses, visual neglect, or vestibular deficits, and 5) inability to complete three step directions.

3.2.1 DATA COLLECTION

Participants began testing by completing three walking trials at a self-selected speed over a 14 foot GaitRite mat (CIR Systems Inc, Havertown, PA). Passive reflective markers were then placed on the calcaneus of each foot and subjects were outfitted with a safety harness that connected to the ceiling overhead to prevent a fall while on the treadmill. The safety harness did not provide body weight support. Subjects were allowed to hold handrails to prevent a loss of balance; however subjects were encouraged to walk without holding the handrails (15/30 subjects held on to handrails during testing). Subjects wore noise-reducing headphones (3M, model: Peltor Optime 105) to reduce auditory cues from differences in treadmill motor output. While on the treadmill, subjects used hand gestures (thumbs up, thumbs down) or verbal responses to communicate with investigators. To prevent participants from using visual information to determine the asymmetry between treadmill belts, a cloth cover was placed from handrail to handrail in front of the subjects during walking. The cover was flexible to allow subjects to move forwards/backwards on the treadmill without impeding gait or providing sensory input with movement on the treadmill. Rest breaks were provided after the completion of five to ten minutes of walking or when necessary.

Subjects walked on an instrumented split-belt treadmill (Bertec Corp, Columbus, OH) at 70% or greater of their comfortable overground gait speed. The treadmill belts moved continuously for periods of five to ten minutes, depending on the physical condition of the subject. Within each period of continuous walking, trials with the treadmill belts moving at different speeds were collected. Each trial consisted of two seconds of walking with the treadmill belts moving at the same speed, a maximum of six seconds of asymmetrical treadmill walking, and a return to walking with the treadmill belts moving at a paired speed. The treadmill belts accelerated/decelerated at a rate 0.50 m/s^2 until reaching the target speed for each belt. A period of at least 20 seconds and visual confirmation that participants had returned to their typical walking pattern with the treadmill belts at the paired speed was employed between trials to limit a carry-over effect to the following trial.

Asymmetry between treadmill belts ranged from 0% difference (symmetrical) to a 70% difference in speed between treadmill belts (0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70% belt speed difference). The maximum belt speed difference was ~2:1 ratio, which has been used previously to induce kinematic gait adaptations in individuals post-stroke (Reisman et al. 2007; Reisman et al. 2010). Differences in treadmill belt speeds were divided between treadmill belts so that the larger magnitude spatiotemporal asymmetry ratio (step length or stance time) during overground walking was augmented when walking on the treadmill. For example, for subjects with greater overground stance time asymmetry, the limb with longer duration in contact with the ground was placed on the slower moving belt for all trials while the other limb stepped on the faster treadmill belt for all trials. For subjects with greater step length asymmetry, the belts were arranged so the limb with the longer step was placed on the slower moving belt. For subjects who had both stance and step length asymmetry, the greater of the two asymmetry ratios was used to determine the treadmill belt/foot combination. During trials in which the treadmill belts moved at different speeds, the difference in speed was divided between the two belts. For example, a 70% belt speed difference was imposed by decreasing the speed of one belt 35%

while increasing the other treadmill belt speed by 35%. Subjects provided a verbal response or a hand gesture when they identified the treadmill belts as moving at different speeds.

To determine the threshold of inter-limb asymmetry awareness and detection, an adaptive stair-case protocol (Figure 1) was employed in which trial responses influenced the magnitude of treadmill belt asymmetry of the following trial (Dyck et al. 1993; Berquin et al. 2010). The staircase design was conducted twice simultaneously with trials alternating between the two stair-cases which gave subjects the impression of a random presentation of trials. In one stair-case, the initial trial was conducted with the largest belt speed difference (70%) and if the subject correctly identified the belts as moving asymmetrically, then the following trial was four levels (5% difference in belt speed between belts per level) of smaller belt speed difference (50%, based on correct response). Responses that continued a trend (correct or incorrect) resulted in a change in belt speed difference of four levels (eg. 70% to 50% to 30%). Responses that resulted in a reversal of a trend (change from increase to decrease in belt speed difference or vice versa) followed a 4, 2, 1 protocol such that belt speed difference was increased or decreased by 4, 2, or 1 levels (20%, 10%, or 5% difference in treadmill belt speeds respectively). The other stair-case was initiated with the minimum difference in belt speeds (5%) with the following trial conducted with a difference in belt speed four levels greater (25%) if the subject was unable to correctly identify the treadmill belts as moving at different speeds. Catch trials were also conducted in which subjects walked with no difference in speed between treadmill belts (0%). A catch trial was completed approximately once in every five (~1/5) trials. The protocol was completed when ten turn-around points at one level change had been conducted. Additional trials were then collected to ensure a minimum of five trials at each belt speed difference level below conscious perception were collected.

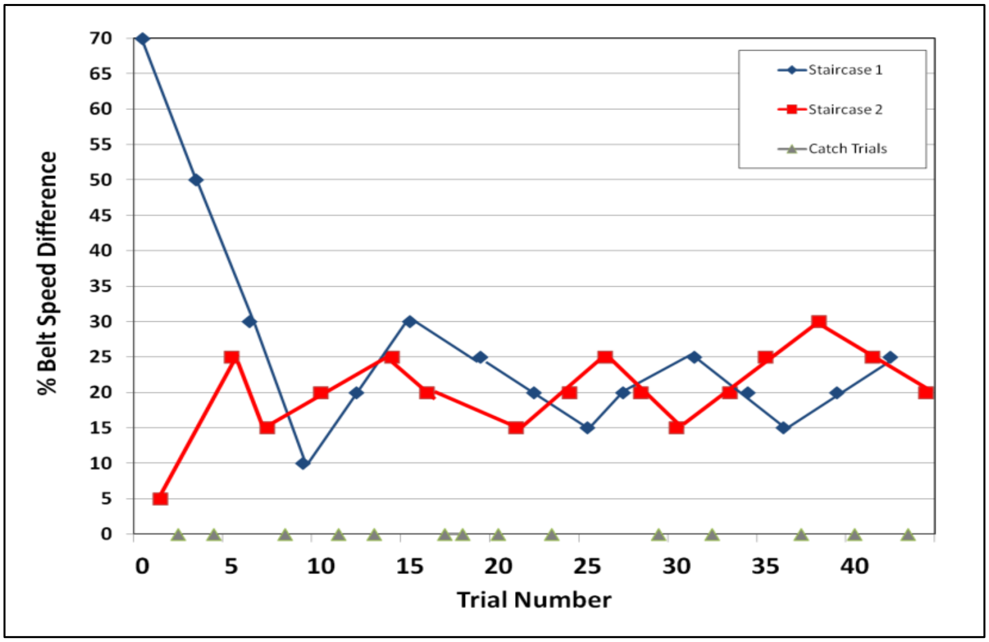

Figure 8. Dual Stair-case design to determine minimum detectable threshold of inter-limb spatiotemporal asymmetry.

Ground reaction force data (vertical, anterior/posterior, and medial/lateral) were collected at a frequency of 1200 Hz and three-dimensional kinematic data were collected at a frequency of 120 Hz. Kinematic data were collected using a passive reflective motion capture system (Nexus 1.4.116, ViCON Corp., Santa Ana, CA) with 14 mm markers placed on both feet.

3.2.2 DATA MANAGEMENT

Spatiotemporal asymmetry ratios (step length, stance time) were calculated for each trial using a custom LabView program. Asymmetry ratios were calculated for the first six steps after the treadmill belts attained the target speeds (three for the paretic and non paretic legs respectively). A maximum of six steps were included for analysis as stance time has been shown to rapidly adapt to changes in gait speed (Reisman et al. 2010). Step length was calculated as the distance in the anterior/posterior direction between the heel marker of the leading foot and the heel marker of the trailing foot. Stance time was calculated as the duration (in seconds) that the limb was in contact with the treadmill belt with a force greater than 50 Newtons. Spatiotemporal asymmetry ratios for step length and stance time were calculated using the following equation:

$$\text{Asymmetry ratio} = \frac{\max(V_{non-par}, V_{par})}{\min(V_{non-par}, V_{par})}$$

where a ratio of one represents symmetry and a ratio greater than one is proportional to the magnitude of asymmetry.

The threshold of awareness was calculated using a subject specific multi-level logistic regression model with difference in treadmill belt speed as a fixed effect coefficient. The threshold was determined as the point where identification of walking asymmetry was greater than 50%. Similarly, multi-level logistic regression models were used to calculate spatiotemporal asymmetry ratios (step length and stance time) at the threshold of awareness (conscious perception). Logistic regression models that included both step length and stance time as fixed effects were derived to determine if one or both coefficients were necessary to identify asymmetry greater than 50%. Based on the output from these models, additional logistic regression models were derived to determine the influence of each fixed effect (step length or stance time) on the prediction of walking asymmetry.

The threshold of detection (subconscious perception) was calculated as the percent of belt speed difference at which walking differed from baseline treadmill walking (when the treadmill belts were moving at equal speed) for step length and stance time respectively for each subject. Additionally, spatiotemporal asymmetry ratios at the threshold at which belt speed difference was detected were calculated for each subject. The threshold of detection (when spatiotemporal asymmetry differed from baseline treadmill walking) for each subject was determined using a repeated measures ANOVA using paired samples t-tests post hoc with an alpha level of p=0.05.

3.2.3 DATA ANALYSIS

Differences in step length and stance time asymmetry ratios between overground walking, at the threshold of detection, and at the threshold of awareness were determined using an analysis of variance with paired student t-tests post hoc with an alpha level of 0.05. Associations between overground walking measures (comfortable gait speed, step length asymmetry ratio, stance time asymmetry ratio) and thresholds of perception (awareness and detection) were determined by calculation of Pearson product correlations. Statistical analyses were conducted using SPSS 16.0 (IBM, Armonk, New York) with an alpha level of 0.05.

3.3 RESULTS

Participants had a self-selected overground comfortable gait speed (CGS) of 0.79±0.21 m/s (range 0.36-1.16m/s) with an average step length asymmetry ratio of 1.13±0.13 (range 1.01-1.60) and stance time asymmetry ratio of 1.14±0.11 (range 1.01-1.37). The average walking speed on the treadmill was 0.70±0.20 m/s (range 0.36-1.16m/s).

Table 5. Individual subject demographic information of study participants.

Subject	Paretic Limb	Gender	Age (years)	Months Post Stroke	AFO	Cane	Holding Rail	Faster Belt
D1	L	F	45	50	yes	no	yes	Left
D2	L	M	69	210	yes	yes	yes	Left
D3	R	F	46	66	no	no	no	Right
D4	L	M	38	56	no	no	no	Right
D5	L	M	79	41	no	no	no	Left
D6	L	M	67	83	no	no	no	Left
D7	L	M	74	28	yes	no	yes	Left
D8	L	M	66	470	no	no	yes	Left
D9	R	F	48	8	no	no	no	Right
D10	R	M	55	32	yes	yes	yes	Right
D11	L	F	43	118	no	no	no	Right
D12	L	M	29	40	yes	yes	yes	Right
D13	L	F	63	56	no	no	yes	Left
D14	R	M	48	15	yes	no	no	Right
D15	R	F	55	53	no	no	no	Right
D16	L	F	61	125	yes	no	yes	Left
D17	R	F	64	34	no	yes	yes	Left
D18	R	M	57	99	no	no	yes	Left
D19	R	F	47	50	no	no	no	Right
D20	R	M	59	107	no	no	no	Left
D21	L	F	61	45	yes	yes	no	Right
D22	L	F	47	95	yes	yes	yes	Right
D23	R	M	59	77	no	no	yes	Right
D24	R	M	70	148	no	no	yes	Right
D25	L	F	58	379	no	no	yes	Right
D26	L	M	75	63	yes	yes	no	Left
D27	L	F	46	257	no	no	yes	Right
D28	R	M	81	142	no	no	yes	Left
D29	L	M	86	67	no	no	no	Right
D30	L	M	62	80	no	no	yes	Right
	Mean	17M	58.60	103.13	10AFO	7Cane	17 Yes	17 Right
	St. Dev	13F	13.36	103.75			13 No	13 Left

Table 6. Individual subject data of treadmill walking speed, overground comfortable gait speed, step length asymmetry ratio, and stance time asymmetry ratios.

		Overground		
Subject	Treadmill Speed (m/s)	Gait Speed (m/s)	Step Length Asymmetry	Stance Time Asymmetry
D1	0.76	0.76	1.06	1.37
D2	0.70	0.85	1.03	1.14
D3	0.70	0.83	1.07	1.19
D4	1.04	1.04	1.17	1.15
D5	0.99	0.99	1.09	1.02
D6	0.75	0.83	1.03	1.12
D7	0.36	0.36	1.03	1.32
D8	0.70	0.91	1.12	1.02
D9	1.16	1.16	1.01	1.01
D10	0.40	0.45	1.04	1.19
D11	0.73	0.73	1.23	1.17
D12	0.75	1.07	1.16	1.14
D13	0.48	0.48	1.08	1.10
D14	0.75	0.75	1.11	1.24
D15	0.90	0.90	1.10	1.11
D16	0.45	0.62	1.03	1.26
D17	0.40	0.56	1.21	1.12
D18	0.62	0.87	1.18	1.16
D19	0.65	0.65	1.05	1.10
D20	0.75	0.92	1.21	1.12
D21	0.55	0.66	1.34	1.37
D22	0.40	0.46	1.60	1.21
D23	0.85	1.00	1.07	1.07
D24	0.75	0.87	1.06	1.02
D25	0.65	0.77	1.21	1.03
D26	0.50	0.56	1.13	1.32
D27	0.75	1.06	1.07	1.06
D28	0.68	0.68	1.37	1.12
D29	1.00	1.11	1.04	1.01
D30	0.93	0.93	1.01	1.04
Mean	0.70	0.79	1.13	1.14
St. Dev	0.20	0.21	0.13	0.11

The average threshold of awareness (conscious perception of asymmetry between treadmill belts) was 22.38±11.07% (range 0.5-47.4). Subconscious detection of walking asymmetry, when walking patterns differed from baseline walking on the treadmill, was 17.88±8.27% for step length and 15.00±8.16% for stance time asymmetry.

Differences in spatiotemporal asymmetry were found between overground walking and at the threshold of detection and at the threshold of awareness for all subjects. A main effect was found for step length (p=0.023) between the step length asymmetry ratios during overground walking, at the threshold of detection and at the threshold of awareness. The step length asymmetry ratios at the threshold of detection (1.19±0.16) and at the threshold of awareness (1.24±0.14) were greater than the step length asymmetry ratio during walking overground at a self-selected speed (1.13±0.13; p=0.032 and p=0.006 respectively). There was no difference in step length asymmetry ratio for all subjects at the threshold of detection and at the threshold of awareness (p=0.150).

There was no main effect for stance time asymmetry ratios between overground walking, at the threshold of detection, and the threshold of awareness (p=0.111). No differences were found for all subjects between stance time asymmetry ratios during overground walking (1.14±0.11) and the ratios at the threshold of detection (1.17±0.12, p=0.379) or the stance time ratio at the threshold of awareness (1.21±0.14; p=0.183). Additionally, there was no difference in stance time asymmetry ratio at the threshold detection and at the threshold of awareness (p=0.321).

Table 7. Step length and Stance time asymmetry ratios during overground walking, at the threshold of detection (subconscious) and at the threshold of awareness (conscious). Mean ± standard deviation. Significant differences ($p<0.05$) between overground walking and perception (awareness or detection) noted by *.

	Step Length Asymmetry Ratio	Stance Time Asymmetry Ratio
Overground	1.13±0.13	1.14±0.11
Detection	1.19±0.16*	1.17±0.12
Awareness	1.24±0.14*	1.21±0.14

Significant correlations were found amongst overground walking measures and perception measures during treadmill walking. Comfortable gait speed was correlated with the detection threshold of step length asymmetry ($r=-0.422$, $p=0.032$) during treadmill walking. Also, overground walking speed was correlated with step length asymmetry and stance time asymmetry ratios at both the threshold of detection and the threshold of awareness. Comfortable gait speed was correlated with step length asymmetry ratio ($r=-0.503$, $p=0.009$) and stance time asymmetry ratio ($r=-0.663$, $p<0.001$) at detection. At the threshold of awareness, stance time asymmetry ratio was correlated with overground walking speed ($r=-0.682$, $p<0.001$).

Step length asymmetry during overground walking was also correlated with measures of perception in people post stroke while walking on the treadmill. Overground step length asymmetry was correlated with the threshold of awareness during treadmill walking ($r=0.411$, $p=0.024$) as well as step length asymmetry ratio at the threshold of awareness ($r=0.423$, $p=0.022$). Overground step length asymmetry was also correlated with step length asymmetry at the threshold of detection ($r=0.781$, $p<0.001$).

Overground stance time asymmetry was found to be correlated with stance time asymmetry ratios at both the threshold of awareness (r=0.579, p=0.001) and the threshold of detection (r=0.774, p<0.001).

Table 8. Pearson product correlations and p values for overground walking measures (comfortable speed, step length asymmetry, stance time asymmetry) and perception (awareness and detection thresholds and asymmetry ratios). Significant correlations (p<0.05) indicated in yellow, near significant correlations indicated in orange (p<0.075).

	Comfortable Gait Speed	Overground Asymmetry Step Length	Overground Asymmetry Stance Time
Detection			
Step Length Threshold	r=-0.422; p=0.032	r=0.142; p=0.490	r=-0.082; p=0.692
Stance Time Threshold	r=-0.340; p=0.077	r=-0.086; p=0.663	r=0.276; p=0.154
Step Length Asymmetry	r=-0.503; p=0.009	r=0.781; p<0.001	r=0.158; p=0.442
Stance Time Asymmetry	r=-0.663; p<0.001	r=-0.093; p=0.639	r=0.774; p<0.001
Awareness			
Threshold	r=-0.337; p=0.068	r=0.411; p=0.024	r=0.115; p=0.546
Step Length Asymmetry	r=-0.346; p=0.066	r=0.423; p=0.022	r=0.106; p=0.586
Stance Time Asymmetry	r=-0.682; p<0.001	r=-0.035; p=0.857	r=0.579; p=0.001

Regression models including step length and stance time asymmetry ratios were used to identify when differences in treadmill belts speed could be predicted at a success rate of 50%. These models identified 12 subjects who predicted belt speed differences based on stance time asymmetry, 11 subjects who predicted asymmetry based on step length asymmetry, four subjects who employed both stance time and step length to identify asymmetry, and three subjects who were determined to use neither stance time or step length asymmetry to identify asymmetry. For the purposes of this study, we examined only those subjects who predicted asymmetry from step length or stance time alone.

Ten of twelve subjects who identified belt speed differences from stance time asymmetry had overground stance time asymmetry (i.e., >1.05) while two other subjects did not present with spatiotemporal asymmetry. Individuals who identified when the belts were moving at different speeds from stance time asymmetry had an average overground stance time asymmetry of 1.17±0.12 and an overground step length asymmetry of 1.09±0.10 with an average overground comfortable gait speed of 0.79±0.22 m/s. The threshold of awareness was 23.90±11.52% belt speed difference and did not differ from individuals who identified awareness using step length asymmetry (23.68±11.42% belt speed difference). Interestingly, there was no difference between the stance time asymmetry ratios overground (1.17±0.12), at the threshold of detection (1.23±0.14), or at the threshold of awareness (1.24±0.15) within the stance time subgroup (p=0.522; p=0.594 respectively). There was however, a difference between overground step length asymmetry ratio and the step length asymmetry ratio at awareness (1.09±0.10 overground, 1.24±0.15; p=0.008).

Of the 11 subjects who identified belt speed differences from step length asymmetry, eight had step length asymmetry overground while three subjects had stance time asymmetry. The average overground step length asymmetry was 1.20±0.16 and an overground stance time asymmetry of 1.15±0.10 with an average overground comfortable gait speed of 0.80±0.21 m/s. Within the step length subgroup, there was no difference between the step length asymmetry ratios overground (1.20±0.16), at the threshold of detection (1.23±0.20), or at the threshold of awareness (1.27±0.14; p=0.734; p=0.912 respectively). There was also no difference between stance time asymmetry ratios overground (1.15±0.10), at the threshold of detection (1.15±0.11), or the threshold of awareness (1.16±0.12 overground, p=0.381, p=0.888 respectively).

3.4 DISCUSSION

The main findings of this study were that to perceive asymmetry people post stroke require an imposed magnitude of spatiotemporal asymmetry that exceeds the ratio they typically walk with and that overground spatiotemporal asymmetry is associated with the perception of asymmetry.

Qualitatively, people post stroke required differences in treadmill belt speeds to perceive the treadmill belts as moving at different speeds. In a study by Lauziere et al (2014), unimpaired elderly adults were capable of perceiving asymmetry and symmetry while walking on a split-belt treadmill at ratios of 0.88 (ascending to asymmetry; ~13% difference in speed between treadmill belts) and 0.85 (descending to symmetry; ~16% difference in speed between treadmill belts) (Lauziere et al. 2014). Although the unimpaired adults were older than the people post stroke in the present study (Lauziere: mean age = 70.9years; present study mean age = 58.6years), perception of asymmetry was identified with smaller differences in treadmill belt speed than the individuals post stroke in the present study. The unimpaired adults did not present asymmetry when walking at a self-selected speed overground (cut-offs identified by Patterson et al (2010 (Patterson et al. 2010)) and may have contributed to a smaller magnitude of asymmetry necessary identification of walking asymmetry. The majority of unimpaired adults self-reported using temporal measures to identify walking asymmetry, despite not typically walking asymmetrically. In the present study, individuals post stroke with overground stance time asymmetry primarily identified belt speed differences using stance time asymmetry whereas people post stroke with overground step length asymmetry primarily identified belt speed differences using step length asymmetry as a predictor. This impaired perception may be due to identifying their established gait patterns as normal and not recognizing more symmetrical walking patterns. These results may have clinical implications for rehabilitation of walking asymmetry, as conscious perception of walking asymmetry is necessary to promote motor learning (Kleim and Jones 2008).

Asymmetrical walking in people post stroke may persist as a result of identifying their asymmetrical gait as normal and they are unable to perceive more symmetrical gait as being more symmetrical. Malone and Bastian (Malone and Bastian 2014) found that during adaptive split-belt treadmill walking, people post stroke adapted back to the spatiotemporal asymmetry ratios identified during overground walking. This suggests that although people post stroke are capable of producing a more symmetrical gait pattern, they are unable to perceive this more symmetrical walking pattern and return to their default spatiotemporal asymmetry. In the present study, conscious perception of differences in treadmill belt speeds occurred when spatiotemporal asymmetry exceeded the default overground spatiotemporal asymmetry in people post stroke.

The movement patterns of people post stroke were modified subconsciously prior to conscious perception of differences in treadmill belt speeds, providing evidence that people post stroke are capable of modification of movement patterns although these differences are not detected from their established ‘normal’ walking pattern. This may be due to differences in how afferent information from the lower extremity is processed consciously and subconsciously. Conscious perception of changes in muscle length or tension is identified when afferent feedback is sent from the lower extremity to the dorsal root ganglion and transferred via the dorsal spinocerebellar tract to the ventral posterior-lateral nucleus of the thalamus where it is then sent to the post central gyrus of the parietal lobe. Alternatively, afferent feedback can also be transferred subconsciously terminating in the cerebellum via the spinocerebellar tract. The difference locations where afferent feedback is sent consciously and subconsciously may determine how locomotor patterns can differ without the individual perceiving the change. Afferent feedback sent to the cerebellum subconsciously is compared to the predicted movement associated with the walking pattern. As afferent information is integrated in the parietal lobe of the cortex, individuals are able to consciously differentiate between the predicted movement and the modified walking pattern that is produced. Small variance from the ‘new normal’ movement pattern in people post stroke would not be perceived consciously and would require larger magnitude differences between the established walking pattern of people post stroke and the altered movement pattern to be perceived.

Small magnitude differences between the established movement pattern post stroke and altered movement patterns may not be large enough in magnitude to be identified as different from the predicted movements following stroke. Instead, small deviations from the anticipated movement may be determined to be noise in the system as a result of impaired motor control or differences in afferent feedback between the paretic and non paretic limbs.

One limitation of the present study is the instructions that were provided to subjects prior to walking on the split belt treadmill. Participants were instructed to identify when the treadmill belts were moving at different speeds rather than when their legs were moving asymmetrically. As a result, conclusions related to the perception of walking asymmetry cannot be made. Therefore the results are limited to the identification of differences in treadmill belt speeds and the respective spatiotemporal asymmetrical movement patterns that accompanied this perception.

3.5 CONCLUSIONS

In conclusion, people post stroke require large discrepancies in speed between treadmill belts to consciously perceive them as moving at different speeds. This may be due to perceiving their established post stroke walking pattern as normal and an inability to consciously perceive small differences in spatiotemporal asymmetry associated with small differences in treadmill belt speed. Additionally, overground spatiotemporal asymmetry is associated with spatiotemporal asymmetry when walking on a split belt treadmill in people post stroke. Further work is necessary to identify the cause of impaired perception of walking asymmetry to further elucidate why people post stroke adopt asymmetrical movement patterns despite the capability of producing symmetrical gait.

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CHAPTER 4:

Manuscript 3 – Lower extremity sensation is not associated with perception of walking asymmetry in people post stroke

4.1 INTRODUCTION

It has been estimated that as many 60% of people post stroke have temporal asymmetry (Patterson et al. 2008a; Patterson et al. 2010) and as many as 49% of people post stroke have spatial asymmetry when walking overground (Patterson et al. 2008a; Patterson et al. 2010). Our research team has previously demonstrated that the persistence of spatiotemporal gait asymmetry in people post stroke may be due to impaired perception of walking symmetry (Wutzke et al. 2014b). Abnormal gait patterns established post stroke appear to be identified as normal, requiring large magnitudes of asymmetry to be perceived as asymmetric (Wutzke et al. 2014b). We previously hypothesized that difficulty in perceiving asymmetrical walking patterns may be influenced by impairments in lower extremity sensation in people post stroke.

Sensory impairment in the lower extremity of people post stroke has been identified in both the acute (Tyson et al. 2008) and chronic (Hsu et al. 2003; Lee et al. 2005; Hillier and Dunsford 2006; Wutzke et al. 2014a) phases of stroke recovery. These impairments, including reduced cutaneous sensation on the plantar surface of the feet and proprioceptive sensation at the ankle and knee, may be due to inappropriate integration of signals in the central nervous system. As a result of this potential misuse of sensory feedback from the lower extremity, people with greater spatiotemporal asymmetry during overground walking may require large magnitudes of asymmetry to perceive differences from established movement patterns.

Inaccurate interpretation of afferent feedback from the lower extremity may contribute to deficits in the perception of walking asymmetry resulting in the shifting of attention to alternative sources of feedback from the lower extremity. In the presence of conflicting sensory information, afferent feedback may be re-weighted with additional weighting on feedback that is identified as correct (Jeka et al. 2010; Polastri et al. 2012). In people post stroke, impairments in lower extremity sensation may lead to increased reliance on sensory feedback from the non paretic limb during gait. Light touch and proprioception as measured by the Fugl-Meyer assessment have been identified as limiting factors for gait function in people with mild to moderate stroke (Hsu et al. 2003); however, the influence of sensory impairments on perception of walking asymmetry requires further study.

Alternatively, there is evidence that sensory impairments in the lower extremity in people post stroke may not affect walking function (Perry et al. 1995). Cutaneous sensation, assessed on the plantar surface of the hallux was determined to have no associations with adaptation to split-belt treadmill walking in people post stroke (Reisman et al. 2009; Malone and Bastian 2014). Movement detection at the hip, knee, ankle and hallux have also been examined to determine the influence of proprioception on walking function (Perry et al. 1995) and the ability to transfer a more symmetrical walking pattern overground after split-belt treadmill walking (Reisman et al. 2009) in people post stroke.

The purpose of this study was to identify associations among lower extremity sensory measures (cutaneous, vibratory, and proprioception) in the paretic and non-paretic limbs and perception of walking asymmetry in people with chronic hemiparesis. We hypothesized that sensory impairments in people with chronic hemiparesis would be associated with deficits in the perception of walking asymmetry.

4.2 METHODS

Thirty people post stroke ($\bar{x}$ age: 58.60±13.36 years, $\bar{x}$ height: 170.31±10.34 cm, $\bar{x}$ weight: 82.70±17.77 kg, 17M/13F, 18 right limb paretic, 12 left limb paretic) were recruited to participate in the study after reading and signing an approved IRB consent document. Inclusion criteria included clinical symptoms (i.e. hemiparesis, impaired motor coordination) of unilateral stroke (ischemic or hemorrhagic) diagnosed by a physician. All participants were at least six months post stroke and used an assistive device or lower extremity bracing (i.e. ankle/foot orthosis) for walking when necessary. Subjects were excluded from participation if they: 1) were unable to walk without physical assistance, 2) had a history of lower extremity joint replacement or injury in the lower extremity, 3) had vision impairments not corrected by lenses, visual neglect, or vestibular deficits, or 4) had communication or cognitive impairments that might interfere with the understanding of the study purpose or procedures and result in an inability to comply with experimenter requests or procedures.

Subjects were screened for unilateral visual neglect (star cancellation test), vision impairments (self-report of visual impairments), lower extremity strength (manual muscle testing of quadriceps, tibialis anterior and gastrocnemius), and vestibular impairments (self-report of vestibular deficits) prior to testing. Lower extremity motor coordination was assessed using the lower extremity portion of the Fugl-Meyer test to score movements at the hip, knee, and ankle in five sections with subcomponents scored on a scale from zero to two (Duncan et al. 1983).

4.2.1 DATA COLLECTION

Assessment of lower extremity sensation has been described previously (Wutzke et al. 2014a). Briefly, sensation was assessed using three different techniques on the paretic and non paretic limbs of all subjects. **Cutaneous sensation** was assessed at the heel, great toe, lateral border of the foot, and base of 1st metatarsal with a set of five Semmes Weinstein monofilaments (2.83, 3.61, 4.31, 4.56 and 6.65g). The threshold of sensation at each site was identified as the minimum gauge of monofilament detected with an accuracy of 80% or greater and included 'catch' trials when the monofilament was not in contact with a foot (Feng et al. 2009). **Vibration sensation** was assessed with a bio-thesiometer (Bio-Medical Instrument Company, Newbury, OH) at the lateral calcaneous, distal phalanx of the hallux, and the medial femoral condyle using the z*ero to threshold* technique. Five trials were completed at each site. **Proprioceptive sensation** was assessed using a movement detection task at the ankle (plantarflexion and dorsiflexion) and knee (flexion and extension) of each limb while seated on a Cybex Norm (CSMi, Stoughton, MA). Three trials were conducted in each direction of movement at each joint. The angular change in position between the starting position and end position, as identified by the subject, was recorded.

The protocol for the perception of belt speed differences during split-belt treadmill walking has been previously reported (Wutzke et al. 2014b). Briefly, as subjects walked on an instrumented split-belt treadmill (Bertec Corp, Columbus, OH) at or near their comfortable overground gait speed, short durations of asymmetric walking were imposed by splitting the speeds of the belts. Asymmetry between treadmill belts ranged from 0% difference (symmetrical) to a 70% difference in speed between treadmill belts (0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70% belt speed difference). Differences in treadmill belt speeds were divided between treadmill belts so that the larger magnitude greater spatiotemporal asymmetry ratio (step length or stance time) during overground walking was augmented when walking on the treadmill. Subjects wore noise-reducing headphones (3M, model: Peltor Optime 105) and used hand gestures (thumbs up, thumbs down) or verbal responses to identify when the treadmill belts were moving at different speeds.

An adaptive, dual stair-case protocol (Dyck et al. 1993) was employed to determine the threshold of conscious perception of differences in speed between the treadmill belts. In one stair-case, the initial trial was conducted with the largest belt speed difference (70%) and the other was initiated with the minimum difference in belt speeds (5%). Subsequent trials followed a 4, 2, 1 protocol where responses that stopped the initial trend were increased/decreased 20% between trials, the second response that reversed a trend was increased/decreased 10%, and subsequent trials that resulted in a reversal were increased/decreased with a 5% change in belt speed. Catch trials were also included where subjects walked with no difference in speed between treadmill belts (0%) at a rate of one in five trials. The protocol was completed when ten turn-around points at one level change had been conducted. Additional trials were then collected to ensure a minimum of five trials at each belt speed difference level below conscious perception were collected.

Ground reaction force data (vertical, anterior/posterior, and medial/lateral) were collected at a frequency of 1200 Hz and three-dimensional kinematic data were collected at a frequency of 120 Hz. Kinematic data were collected from 14 mm markers placed on the calcaneus of each foot using passive reflective markers and a motion capture system (Nexus 1.4.116, Vicon Corp., Santa Ana, CA).

4.2.2 DATA MANAGEMENT

Lower extremity sensory data was managed similarly to Wutzke et al, 2014 (Wutzke et al. 2014a). Cutaneous sensation at each location on the paretic and non paretic foot were converted to a rank scale (e.g., 1 to 6) corresponding to the monofilament with the least force that was detected with an accuracy equal or greater to 80%. Six values for vibratory sensation were calculated as the average score for each of the three sites (hallux, calcaneous, and medial femoral condyle) on each limb (paretic and non paretic) using the zero to threshold technique. Proprioceptive sensation was calculated as the angular deviation for each movement direction (plantarflexion/dorsiflexion) at the ankle or knee (flexion/extension) of the paretic and non-paretic limbs.

Variables derived during split-belt treadmill walking were managed similarly to Wutzke et al 2014 (Wutzke et al. 2014b). Spatiotemporal asymmetry ratios (step length, stance time) were calculated from the first six steps after the treadmill belts reached their target speeds (three for the paretic and non paretic legs respectively). Step length was calculated at the distance in the anterior/posterior direction between the heel marker of the leading foot and the heel marker of the trailing foot. Stance time was calculated as the duration (in seconds) that the limb was in contact with the treadmill belt with a force greater than 50 Newtons.

The threshold of awareness was calculated using a subject specific multi-level logistic regression model with difference in treadmill belt speed as a fixed effect coefficient and multi-level logistic regression models were used to calculate spatiotemporal asymmetry ratios (step length and stance time) at the threshold of awareness (conscious perception). Output from these models were used to then employ additional logistic regression models to determine the influence of each fixed effect (step length or stance time) on the prediction of walking asymmetry.

4.2.3 DATA ANALYSIS

Subjects were grouped on the basis of the results of regression models to identify the spatiotemporal asymmetry (step length or stance time) used to predict differences in treadmill belt speed. Twelve subjects were identified who used stance time asymmetry to predict belt speed differences and eleven subjects who predicted asymmetry in belt speed based on step length asymmetry. Four subjects were identified who used both stance time and step length to predict differences in belt speeds and three subjects used neither stance time nor step length asymmetry to identify asymmetry. For the purposes of this study, we examined only those subjects (n=23) who predicted asymmetry from step length or stance time alone.

Associations between measures of perception (awareness threshold, step length asymmetry ratio, stance time asymmetry ratio at awareness) and measures of lower extremity sensation (cutaneous X 8, vibration X 6, proprioception X8) were determined by calculation of partial correlation coefficients controlling for the spatiotemporal asymmetry used to predict belt speed asymmetry within the respective subgroups. Spatiotemporal asymmetry was identified as a covariate as the threshold of conscious perception has been found to be related to spatiotemporal asymmetry. Spearman rank correlations were also conducted to identify associations among scores for the lower extremity Fugl Meyer assessment of coordination and measures of perception for the entire cohort (n=30). Statistical analyses were conducted using SPSS 16.0 (IBM, Armonk, New York) with an alpha level of 0.05.

4.3 RESULTS

Subjects who identified belt speed differences using step length asymmetry were found to have correlations between lower extremity sensation and conscious perception when controlling for baseline step length asymmetry on the treadmill (Tables 9, 10). Cutaneous sensation at the paretic heel was correlated with the threshold of awareness (r=-0.728, p=0.026). No other associations were identified on the paretic limb with measures of awareness. On the non paretic limb, cutaneous sensation of the lateral border was found to be associated with the threshold of awareness (r=0.694, p=0.038). Vibration sensation and proprioception were not associated with conscious perception of asymmetry in people who predicted asymmetry in belt speed using step length asymmetry.

Table 9. Partial correlation coefficients (covariate: baseline step length asymmetry) and p values between measures of awareness (threshold, step length asymmetry, and stance time asymmetry) and measures of lower extremity sensation in the paretic limb of step length asymmetry subgroup. Significant correlations indicated in yellow (p<0.05); near significant correlations indicated in orange (p<0.075).

Paretic Limb		**Awareness**	
Cutaneous	**Threshold**	**Step Length Asymmetry**	**Stance Time Asymmetry**
Hallux	r=-0.256; p=0.506	r=-0.467; p=0.205	r=-0.194; p=0.617
Lateral Border	r=-0.310; p=0.417	r=-0.597; p=0.090	r=-0.232; p=0.548
Heel	r=-0.728; p=0.026	r=-0.588; p=0.096	r=-0.071; p=0.857
Base of 1st Met	r=-0.387; p=0.303	r=-0.521; p=0.150	r=-0.074; p=0.849
Vibration			
Calcaneous	r=-0.045; p=0.908	r=0.000; p=1.000	r=-0.469; p=0.202
Hallux	r=-0.143; p=0.713	r=-0.232; p=0.549	r=-0.427; p=0.251
Medial Femoral Condyle	r=-0.516; p=0.155	r=-0.201; p=0.605	r=-0.075; p=0.848
Proprioception			
Ankle Plantarflexion	r=-0.330; p=0.416	r=-0.425; p=0.254	r=-0.396; p=0.291
Ankle Dorsiflexion	r=-0.311; p=0.416	r=-0.452; p=0.222	r=-0.403; p=0.283
Knee Extension	r=-0.236; p=0.541	r=-0.236; p=0.542	r=-0.320; p=0.401
Knee Flexion	r=-0.362; p=0.338	r=-0.379; p=0.314	r=-0.269; p=0.485

Table 10. Partial correlation coefficients (covariate: baseline step length asymmetry) and p values between measures of awareness (threshold, step length asymmetry, and stance time asymmetry) and measures of lower extremity sensation in the non paretic limb of step length asymmetry subgroup. Significant correlations indicated in yellow (p<0.05); near significant correlations indicated in orange (p<0.075).

Non Paretic Limb	Awareness		
Cutaneous	**Threshold**	**Step Length Asymmetry**	**Stance Time Asymmetry**
Hallux	r=0.337; p=0.376	r=-0.078; p=0.843	r=-0.283; p=0.460
Lateral Border	r=0.694; p=0.038	r=-0.107; p=0.783	r=-0.447; p=0.227
Heel	r=-0.330; p=0.386	r=-0.192; p=0.621	r=-0.242; p=0.531
Base of 1st Met	r=-0.006;p=0.988	r=0.313; p=0.379	r=0.047; p=0.904
Vibration			
Calcaneous	r=0.429; p=0.249	r=0.111; p=0.776	r=-0.583; p=0.099
Hallux	r=0.334; p=0.379	r=-0.032; p=0.935	r=-0.438; p=0.238
Medial Femoral Condyle	r=-0.073; p=0.852	r=-0.048; p=0.902	r=-0.191; p=0.623
Proprioception			
Ankle Plantarflexion	r=-0.139; p=0.338	r=-0.051; p=0.897	r=0.159; p=0.709
Ankle Dorsiflexion	r=-0.370; p=0.327	r=-0.230; p=0.552	r=0.270; p=0.482
Knee Extension	r=0.322; p=0.398	r=0.158; p=0.685	r=-0.140; p=0.719
Knee Flexion	r=0.548; p=0.126	r=0.363; p=0.336	r=0.199; p=0.608

Measures of lower extremity sensation on the non paretic limb were correlated with perception in subjects who identified belt speed differences using stance time asymmetry when controlling for baseline stance time asymmetry during treadmill walking (Tables 11, 12). Cutaneous sensation at the hallux (r=-0.743, p=0.014) and lateral border (r=-0.724, p=0.018) on the non paretic limb were correlated with stance time asymmetry at awareness. Although vibration sensation in the non paretic limb was not found to be correlated with conscious perception, proprioceptive sensation of knee flexion was associated with awareness of stance time asymmetry in the non paretic limb (r=-0.642, p=0.045). No associations were identified among measures of sensation on the paretic limb and conscious perception of asymmetry.

Table 11. Partial correlation coefficients (covariate: baseline stance time asymmetry) and p values between measures of awareness (threshold, step length asymmetry, and stance time asymmetry) and measures of lower extremity sensation in the non paretic limb of stance time asymmetry subgroup. Significant correlations indicated in yellow (p<0.05); near significant correlations indicated in orange (p<0.075).

Non Paretic Limb	Awareness		
Cutaneous	**Threshold**	**Step Length Asymmetry**	**Stance Time Asymmetry**
Hallux	r=0.067; p=0.854	r=0.260; p=0.467	r=-0.724; p=0.014
Lateral Border	r=0.178; p=0.623	r=-0.228; p=0.526	r=-0.724; p=0.018
Heel	r=-0.033; p=0.928	r=-0.190; p=0.599	r=-0.530; p=0.115
Base of 1st Met	r=-0.007;p=0.985	r=0.313; p=0.379	r=-0.412; p=0.237
Vibration			
Calcaneous	r=0.223; p=0.536	r=0.484; p=0.156	r=-0.261; p=0.467
Hallux	r=0.168; p=0.642	r=0.073; p=0.841	r=0.417; p=0.230
Medial Femoral Condyle	r=0.093; p=0.798	r=0.247; p=0.492	r=-0.154; p=0.671
Proprioception			
Ankle Plantarflexion	r=0.053; p=0.884	r=0.105; p=0.774	r=-0.135; p=0.709
Ankle Dorsiflexion	r=-0.341; p=0.335	r=-0.036; p=0.921	r=-0.608; p=0.062
Knee Extension	r=-0.340; p=0.336	r=-0.026; p=0.944	r=-0.606; p=0.064
Knee Flexion	r=0.037; p=0.920	r=0.030; p=0.935	r=-0.642; p=0.045

Table 12. Partial correlation coefficients (covariate: baseline stance time asymmetry) and p values between measures of awareness (threshold, step length asymmetry, and stance time asymmetry) and measures of lower extremity sensation in the paretic limb of stance time asymmetry subgroup. Significant correlations indicated in yellow (p<0.05); near significant correlations indicated in orange (p<0.075).

Paretic Limb	Awareness		
Cutaneous	**Threshold**	**Step Length Asymmetry**	**Stance Time Asymmetry**
Hallux	r=0.042; p=0.909	r=0.337; p=0.341	r=-0.008; p=0.982
Lateral Border	r=0.145; p=0.690	r=-0.119; p=0.744	r=-0.355; p=0.314
Heel	r=-0.211; p=0.559	r=-0.000; p=0.999	r=-0.607; p=0.063
Base of 1st Met	r=-0.085; p=0.816	r=0.170; p=0.639	r=-0.273; p=0.446
Vibration			
Calcaneous	r=-0.010; p=0.979	r=0.087; p=0.810	r=-0.507; p=0.134
Hallux	r=-0.269; p=0.453	r=-0.128; p=0.724	r=-0.208; p=0.564
Medial Femoral Condyle	r=-0.079; p=0.827	r=-0.029; p=0.937	r=-0.402; p=0.249
Proprioception			
Ankle Plantarflexion	r=-0.159; p=0.661	r=-0.145; p=0.689	r=0.268; p=0.453
Ankle Dorsiflexion	r=-0.175; p=0.628	r=-0.040; p=0.912	r=-0.016; p=0.966
Knee Extension	r=-0.211; p=0.558	r=-0.100; p=0.782	r=0.313; p=0.378
Knee Flexion	r=-0.182; p=0.616	r=-0.106; p=0.772	r=0.088; p=0.810

Score on the lower extremity Fugl Meyer assessment were associated with perception of spatiotemporal asymmetry, dependent upon the type of asymmetry used to identify asymmetry on the treadmill. Subjects who used step length to identify asymmetry had associations between Fugl Meyer score and the awareness of step length asymmetry (r=-0.628, p=0.039) whereas subjects who used stance time asymmetry to identify differences between the belts had a correlation between awareness of stance time asymmetry and lower extremity Fugl Meyer score (r=-0.675, p=0.016).

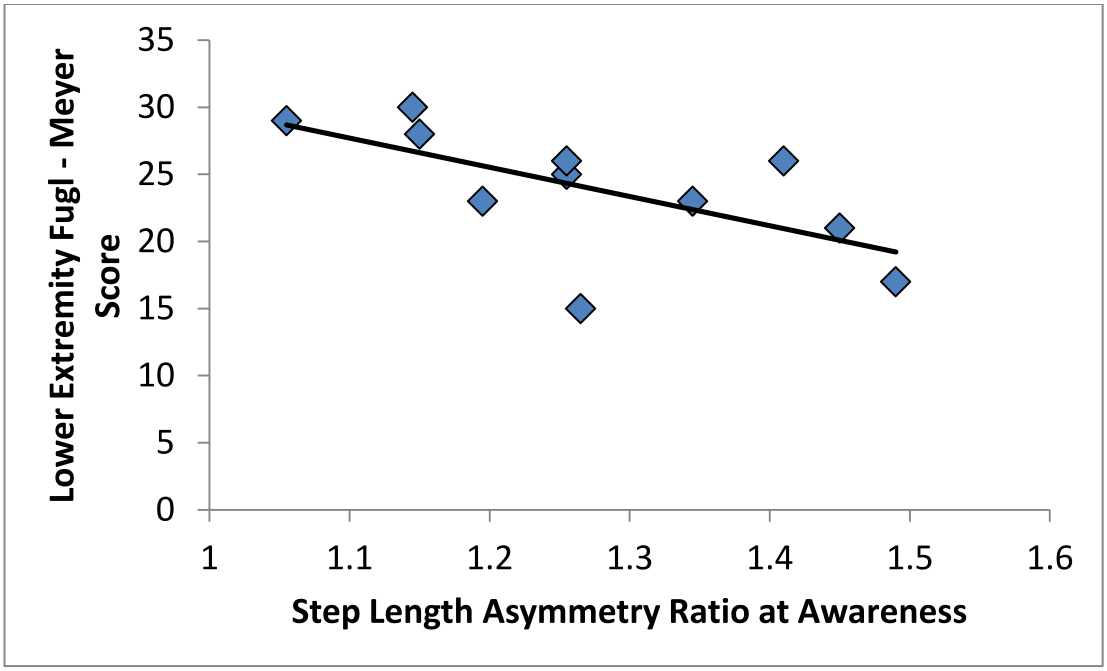

Figure 9 Correlation between step length asymmetry ratio at threshold of awareness and lower extremity Fugl-Meyer score in people post stroke that predicted walking asymmetry using step length.

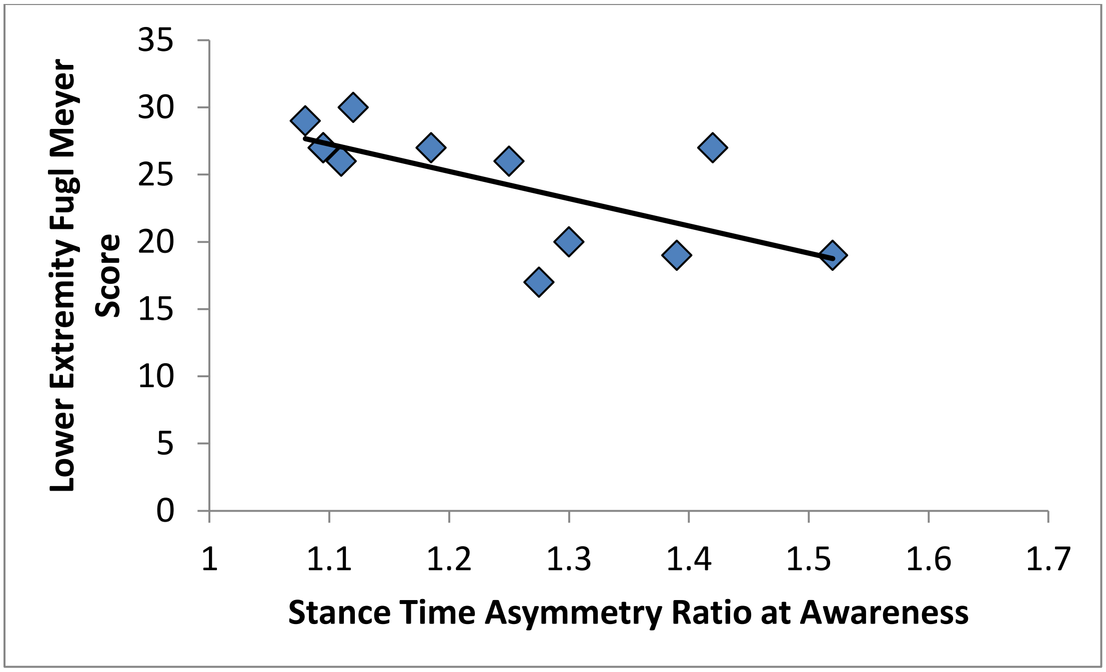

Figure 10. Correlation between overground stance time asymmetry ratio and lower extremity Fugl-Meyer score in people post stroke that predicted walking asymmetry using step length.

4.4 DISCUSSION

The data from this study do not support our hypothesis that lower extremity sensation is associated with conscious perception of walking asymmetry in people with chronic hemiparesis. Although some correlations were identified among measures of lower extremity sensation and conscious perception of asymmetry, the results of this study suggest that lower extremity sensation is not related to an inability to perceive asymmetry. Interestingly, motor coordination as determined by lower extremity Fugl-Meyer score was associated with perception of asymmetry in people with chronic hemiparesis.

Although lower extremity sensation has been shown to occur in people with chronic hemiparesis (Wutzke et al. 2014a), impaired sensation in the lower extremity may lead to increased dependence on afferent information from alternative sources of feedback to perceive walking asymmetry. The negative correlations found in the present study suggest that the types of lower extremity sensation assessed do not impair the perception of walking asymmetry in people post stroke. However, alternative forms of afferent feedback from the lower extremity may provide sufficient information for people post stroke to perceive walking asymmetry. Therefore, perception of walking asymmetry may become more easily identified despite greater impairments in lower extremity sensation.

Re-weighting of sensory feedback has been suggested to maintain postural control in the presence of altered visual or proprioceptive feedback (Carver et al. 2006; Jeka et al. 2010; Polastri et al. 2012). For example, in conditions when visual information is inaccurate, Logan et al (2010) suggested that adults will shift priority to sensory feedback that is determined to be more accurate during walking (Logan et al. 2010). In the present study, sensory feedback from the lower extremity that may be incorrectly interpreted in the central nervous system may have reduced priority and alternative sources of feedback (i.e. proximal sensory feedback from the hip, vision) have increased importance.

Despite the hypothesis proposed for this study, there is evidence that impaired lower extremity sensation may not be related to walking function in people post stroke. Proprioceptive sensation (assessed using a movement detection task) at the hip, knee, ankle, and toe was found to be not associated with walking function (Perry et al. 1995) or the ability to produce a more symmetrical movement pattern following augmented asymmetry treadmill walking (Reisman et al. 2009). Additionally, no association has been identified between cutaneous sensation at the plantar surface of the paretic hallux and adaptation to walking with augmented spatiotemporal asymmetry (Reisman et al. 2009; Malone and Bastian 2014).

Although lower extremity sensation was not associated with awareness of asymmetry, motor coordination, as assessed by the lower extremity Fugl-Meyer, was associated with perception. Motor coordination may be associated with perception of walking asymmetry as the control of the lower extremity across multiple joints (hip, knee, and ankle) is necessary to produce a functional gait pattern. Impaired timing and coordination of muscle activity necessary to produce coordinated movements are present in people post stroke (Neckel et al. 2006; Hidler et al. 2007; Clark et al. 2009; Kautz et al. 2011) and may influence perception of asymmetry. Individuals with more significant impairments in motor control may identify asymmetric gait movements in the lower extremity as normal, thereby requiring large differences in asymmetry to be perceived. Compared to unimpaired adults, people post stroke have difficulty coordinating movements at the hip and ankle appropriately during walking (Varoqui et al. 2010). As difficulty in producing appropriate movements in the lower extremity during walking becomes greater in people post stroke, additional attentional demands may be necessary to oversee other aspects of walking, potentially reducing resources available for perceiving asymmetry. Coordinated muscle activity at the hip and knee during toe off and heel contact, necessary for walking in people post stroke, is impaired in people post stroke and has been identified as a mitigating factor in determining gait speed (Daly et al. 2007).

Hsu et al (2003) identified spasticity at the ankle plantarflexors as the primary factor associated with asymmetry in people with mild to moderate stroke (Hsu et al. 2003). Although none of the 26 participants were identified as having severe spasticity at the ankle, impaired control at the ankle (spasticity) was the identified as the greatest contributing factor to spatiotemporal asymmetry (Hsu et al. 2003). In the present study, individuals with impaired motor coordination required greater asymmetry to be perceived. Regardless of the type of spatiotemporal asymmetry (stance time or step length) individuals with a lower score on the lower extremity Fugl-Meyer required larger magnitude of asymmetry to be consciously perceived.

4.5 CONCLUSIONS

In conclusion, lower extremity sensation in the paretic and non paretic limbs of people with chronic hemiparesis is not associated with conscious awareness of walking asymmetry on a split-belt treadmill. This may be due to inappropriate integration of sensory feedback from the paretic lower extremity and therefore increased reliance on alternative sources of feedback to provide information regarding movement of the legs. Associations were identified between motor coordination and perception of asymmetry. Individuals with impaired motor coordination required increased magnitude of belt speed differences and spatiotemporal asymmetry to be perceived. Further work is necessary to explore re-weighting of sensory feedback from the lower extremity and its influence on perception of walking asymmetry in people with chronic hemiparesis.

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CHAPTER 5:

Synthesis

5.1: SUMMARY OF RESULTS

Specific Aim 1: To identify differences in lower extremity sensation (cutaneous, vibration, and proprioceptive sensation) between paretic and non paretic limbs and to identify associations among measures of lower extremity sensation and overground gait measures (comfortable gait speed, step length asymmetry, stance time asymmetry) in people with chronic stroke.

Hypothesis: The paretic limb of people post stroke will have impaired sensation in the lower extremity compared to the non paretic limb and measures of lower extremity sensation (cutaneous, vibration, and proprioceptive sensation) will be correlated with overground gait speed and spatiotemporal asymmetry ratios (step length, stance time) in people post stroke in that individuals with intact lower extremity sensation will have little overground spatiotemporal asymmetry while individuals with impaired sensation will have greater spatiotemporal asymmetry.

The three techniques to assess lower extremity sensation indicated differences between the paretic and non paretic limbs of people with chronic hemiparesis. Each of the four cutaneous sites examined indicated differences between the paretic and non paretic feet of people with chronic hemiparesis. Vibration sensation identified differences in sensation at the heel and medial femoral condyle between the paretic and non paretic limbs while differences in proprioception were evident in both the ankle and knee.

The hypothesis that lower extremity sensation is correlated with gait measures was supported in that measures of lower extremity sensation in people with chronic hemiparesis were correlated with walking function. However, the direction of these correlations suggest that alternative sources of feedback (i.e. vision, proximal lower extremity afferent feedback) may have a greater influence on measures of overground walking as sensory feedback from the lower extremity in people posts stroke may not be interpreted appropriately. Although correlations were identified among gait measures and the non paretic foot including at the lateral border, hallux, calcaneous and medial femoral condyle, the direction of these associations differed from the hypothesized positive correlations between lower extremity sensation and gait measures.

Specific Aim 2: To identify associations among perception (conscious awareness and subconscious detection) of inter-limb asymmetry during treadmill walking and overground walking function (gait speed, step length asymmetry, stance time asymmetry) in people with chronic stroke.

Hypothesis: Perception of inter-limb asymmetry during treadmill walking in people post stroke will be positively correlated with overground walking function (gait speed, step length, stance time asymmetry) in that individuals that perceive small differences in belt speed between treadmill belts will have mild impairments in gait function whereas individuals that perceive only large magnitude differences in speed between treadmill belts will have impaired walking function (slower gait speed overground, increased spatiotemporal asymmetry).

This hypothesis was supported as the magnitude of step length asymmetry necessary to be perceived when walking on the split-belt treadmill needed to exceed the magnitude of step length asymmetry that individuals post stroke walked with overground. However, perception of stance time asymmetry when walking on the split-belt treadmill did not differ from stance time asymmetry when walking overground. Additionally, people post stroke utilized information to identify walking asymmetry differently based on overground spatiotemporal asymmetry. In the present study, the majority (23/30 participants) of individuals utilized step length asymmetry or stance time asymmetry to identify differences in speed between the treadmill belts.

Compared to a study to determine the ability to identify asymmetry in unimpaired adults during treadmill walking (Lauziere et al. 2014), people post stroke required a greater magnitude of asymmetry to be perceived. This impaired perception (qualitatively compared to unimpaired adults) may be due to the processing of feedback necessary to identify differences between the predicted gait pattern established following stroke (the new normal gait pattern) and the altered walking pattern produced with small magnitude differences in speed between treadmill belts.

Although some people post stroke have the necessary strength and coordination to produce a more symmetrical gait pattern, they may select an asymmetrical walking pattern as they may be unable to perceive small differences in asymmetry and return to their default spatiotemporal asymmetry. This return to established spatiotemporal asymmetry was found in a study by Malone and Bastian (Malone and Bastian 2014) in that during adaptive split-belt treadmill walking, people post stroke returned to the spatiotemporal asymmetry ratios identified during overground walking. This may be due to the inability to identify differences between predicted movements and the altered movement pattern therefore people post stroke maintain the established asymmetrical movement pattern.

Specific Aim 3: To identify associations among perception (conscious awareness and subconscious detection) of inter-limb asymmetry during treadmill walking and lower extremity sensation (cutaneous, vibratory and proprioceptive sensation) in people with chronic stroke.

Hypothesis: Lower extremity sensation (cutaneous, vibratory, and proprioception) will be negatively correlated with perception of inter-limb asymmetry during treadmill walking in people post stroke in that individuals with intact lower extremity sensation will be capable of perceiving small inter-limb spatiotemporal asymmetry when treadmill walking.

This hypothesis was supported as conscious and subconscious perception was negatively associated with measures of lower extremity sensation. Interestingly, of the nine correlations that were statistically significant, seven were associations that included a measure of sensation on the non paretic limb. Increased reliance on non paretic feedback may be due to an inability of the central nervous system to appropriately interpret afferent information from the paretic limb. This is similar to an increased reliance on visual or proprioceptive information when sources of feedback are not reliable (Carver et al. 2006; Polastri et al. 2012). Cutaneous sensation at the lateral border of the non paretic foot was correlated with awareness (r=-0.482, p=0.008) and detection of stance time asymmetry (r=-0.384, p=0.043), and proprioceptive plantarflexion sensation at the non paretic ankle was also associated with the stance time threshold of detection (r=-0.392, p=0.039). Vibratory sensation of the non paretic heel (zero to threshold) was correlated with stance time asymmetry at awareness (r=-0.389, p=0.037).

The threshold of step length detection was associated with measures of sensation on both the paretic and non paretic foot. On the paretic foot cutaneous sensation on the hallux (r=-0.404, p=0.040), and vibration sensation at the heel (zero to threshold, r=-0.416, p=0.034) were associated with the threshold of step length detection. On the non paretic limb, vibration sensation at the heel (zero to threshold, r=-0.396, p=0.045) and hallux (zero to threshold, r=-0.430, p=0.028; maximum to threshold, r=-0.389, p=0.050) were associated with the threshold of step length detection.

5.2: INFLUENCE OF STUDY RESULTS AND IMPLICATIONS

The results of this dissertation provide evidence that fills gaps in the existing literature of sensation in the lower extremity of people post stroke and the influence of sensation on perception of walking asymmetry.

A key finding of this dissertation is evidence that people with chronic hemiparesis have impaired sensation in the lower extremity. Impaired sensation in the lower extremity of people post stroke can be identified as a “central processing issue” as the inaccurate integration of afferent feedback, rather than inappropriate or inaccurate sensory feedback ascending to the central nervous system as being the cause of such impairments. Wutzke et al (in process) identified differences in lower extremity sensation in people post stroke and people with bilateral peripheral neuropathy and its association with measures of balance (Wutzke et al. 2014). Although people with bilateral peripheral neuropathy had more severe lower extremity sensory impairments, they exhibited better static and dynamic balance compared to people post stroke. While differences in lower extremity strength and coordination exist between people with bilateral peripheral neuropathy and people post stroke, the inability to process sensory information from the lower extremity appropriately may contribute to impaired motor responses in people post stroke. Lower extremity sensory impairment in people post stroke has previously been examined in the acute phase following stroke (Kim and Choi-Kwon 1996; Tyson et al. 2008) however, this is the first study to assess multiple types of sensation at multiple sites in the lower extremity of people with chronic hemiparesis. This study identified cutaneous, vibratory, and proprioceptive impairments in the lower extremity in people with chronic hemiparesis. More specifically, this study assessed sensation at multiple sites (four cutaneous sites per foot, three sites for vibratory assessment, two sites for proprioceptive sensation) and used multiple techniques and directions of movement to assess vibratory and proprioceptive sensation respectively. Studies that have previously examined sensory impairment in the lower extremity of people with chronic hemiparesis included small sample sizes (Hillier and Dunsford 2006; Lynch et al. 2007) or assessments that would include a single testing site (Lee et al. 2005). The results of this study will provide a foundation for the future assessment of sensation in the lower extremity in people with chronic hemiparesis.

The perception of asymmetry, by identifying differences in speed between treadmill belts and methods to predict spatiotemporal gait asymmetry are findings with significant implications. Conscious perception of differences in speed between treadmill belts required walking asymmetry that exceeded the spatiotemporal gait asymmetry the individual typically presents during overground walking. This is a significant finding as this study is the first to identify the magnitude of asymmetry necessary for conscious and subconscious perception. Lauziere et al (2014) (Lauziere et al. 2014) used different methods to identify the magnitude of asymmetry necessary for unimpaired older adults to perceive asymmetry and the results of this study suggest that people with chronic hemiparesis require larger magnitudes of belt speed difference to identify asymmetry. This may be the result of differences that are sufficient in magnitude between predictions of walking patterns based on the ‘new normal’ established following the stroke and the altered movement pattern due to the difference in speed between the treadmill belts. The difference between the two movement patterns are large enough to be perceived in the central nervous system. Additionally, people post stroke who exhibit spatiotemporal asymmetry overground appear to use their asymmetric measure to identify when walking was asymmetric. For example, someone with stance time asymmetry overground uses stance time asymmetry to predict when the treadmill belts are moving asymmetrically. This is the initial evidence that perception of walking asymmetry may be influenced by the spatiotemporal asymmetry an individual exhibits during overground walking.

The influence of lower extremity sensation on perception of asymmetry in people with chronic hemiparesis is a third important finding stemming from this dissertation. It was revealed that sensory measures in the paretic and non paretic lower extremity are negatively associated with perception of walking asymmetry. The direction of the associations between lower extremity sensation and perception of walking asymmetry suggest that people post stroke may utilize other sources of afferent feedback to identify walking asymmetry. This suggests that impaired afferent feedback may be re-weighted in the central nervous system to place greater importance on feedback from other sources, such as proprioceptive sensation at the hip. Although previous research has investigated the influence of lower extremity sensation on walking function in people post stroke, this is the first study to suggest that lower extremity sensation is not related to perception of walking symmetry. Jeka and colleagues have investigated re-weighting of sensory feedback in unimpaired adults when presented with conflicting visual and proprioceptive information (Jeka et al. 2010; Logan et al. 2010; Polastri et al. 2012); however this is the first study to indicate that the central nervous system may prioritize sensation from sources other than the distal lower extremity to identify walking asymmetry in people post stroke.

5.3: STRENGTHS AND WEAKNESSES

A strength of the current study is the comprehensive assessment of sensation in the lower extremity of people with chronic hemiparesis. Previously a single source of sensory feedback (i.e. cutaneous sensation or proprioception) was investigated in people post stroke. Additionally, most studies would examine sensation at a single site (great toe or heel light touch) or assess sensation as present or absent. The present study examined four sites for cutaneous sensation, three sites for vibration sensation, and two sites for proprioceptive sensation in two directions.

A second strength of the study is the adaptive dual stair-case design utilized to identify the perception of differences in treadmill belt speed during split-belt treadmill walking. The study design limited the ability of participants to identify differences in treadmill belt speed based on time spent walking, instead providing subjects with a presentation of asymmetry that appeared random. In a study completed by Lauziere (Lauziere et al. 2014), walking asymmetry was assessed by walking symmetrically and then uniformly towards asymmetry and initiating walking with a very asymmetrical walking pattern and then uniformly moving towards symmetry. In each condition, participants could have indicated asymmetry or symmetry prior to actually perceiving it. The current study limited the ability to predict when the treadmill belts were moving at the same speed or different speeds.

Weaknesses of the study include instructions provided to subjects prior to walking on the treadmill and the velocity of passive movement to assess proprioceptive sensation. Participants were instructed to identify when the treadmill belts were moving at different speeds. This instruction was used in place of identifying asymmetrical walking to prevent subjects from keying on spatial or temporal aspects of how they walked on the treadmill. Instead, by instructing participants to identify when the treadmill belts were moving at different speeds as a correlate to walking asymmetry, the current study cannot make definitive conclusions on the ability of people with chronic hemiparesis to identify walking asymmetry. Also, proprioceptive sensation was assessed at the knee and ankle with a velocity of one degree per second. This velocity was selected after pilot testing indicated a velocity of 0.5 degrees per second could not be identified. Existing literature indicates that a lower speed provides greater resolution, however a study that examines the influence of multiple passive velocities is necessary to elucidate the influence of faster passive velocities on proprioceptive sensation in people with chronic hemiparesis.

An additional weakness of the study was that lower extremity sensation was not assessed subconsciously which may be important for determining the influence of lower extremity sensation on the subconscious perception (detection) of walking asymmetry. Conscious perception of lower extremity sensation was assessed as individuals provided conscious responses to identify when the monofilament was in contact with the plantar surface of the foot (cutaneous), when the amplitude of vibration was present or no longer present (vibratory sensation), or the position of the ankle or knee when movement was perceived (proprioception). As indicated previously, conscious and subconscious afferent information is integrated differently in the central nervous system and each may provide unique evidence regarding the influence of lower extremity sensation on the perception of walking asymmetry.

5.4: FUTURE DIRECTIONS

The results of this study provide evidence that sensory impairment persists beyond the acute phase of rehabilitation in people post stroke. Additional studies are necessary to identify the prevalence of such sensory impairments in this population. Based on the results of the current study, lower extremity sensory impairment is common in people in the chronic phase of hemiparesis, potentially equal to the percentage of people post stroke that demonstrate sensory impairment acutely (approximately 60%; (Tyson et al. 2008)). Furthermore, proprioceptive sensation and the influence on walking function in people post stroke requires additional study. Examination of the influence of passive movement velocity in people with chronic hemiparesis is necessary to improve our understanding of proprioceptive impairments in people post stroke and the influence proprioception has on walking function post stroke.

Finally, the contribution of specific sources of afferent feedback (cutaneous, proprioceptive) in people post stroke remains an area of further study. The contribution and re-weighting of sensory information (vision, proprioception) has been previously explored in unimpaired adults during walking (Logan et al. 2010) and standing (Polastri et al. 2012); however, the re-weighting of afferent information in people post stroke may provide additional insight as to the use of feedback in this population during walking which may have clinical implications.

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