The Role of Cutaneous Receptors on the Dorsal Ankle Joint during Locomotion

by

Erika E. Howe

A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
For the degree of
Master of Science
in
Human Health and Nutritional Science and Neuroscience

Guelph, Ontario, Canada

©Erika Howe, July 2013
ABSTRACT

THE ROLE OF CUTANEOUS RECEPTORS ON THE DORSAL ANKLE JOINT DURING LOCOMOTION

Erika E. Howe
University of Guelph, 2013

Advisor:
Dr. Leah R. Bent

The aim of the current thesis was to explore the proprioceptive role of dorsal foot skin and its influence on the joint kinematics of gait strategies during, normal level walking (Experiment I) as well as during adaptive gait while crossing an obstacle (Experiment II). Twelve volunteer’s kinematic data were recording during walking trials for each experiment. Test conditions included sensory interventions which either reduced skin input (via topical anesthetic), visual input (via lower occlusion goggles) or simultaneously manipulated both skin and vision. Our results show that ankle control in gait relies on feedback from skin overlaying the joint. In level walking, anesthetic produced significant angular changes in the ankle and knee joints but no changes to minimal toe clearance (MTC). With the lead limb anesthetized, toe clearance (TC) while crossing the obstacle was increased. Conversely, anesthetizing the trailing limb had no effect on any joint positions or toe trajectory parameters. The acute loss of skin input in healthy young adults resulted in involvement for ankle and knee joint position sense however were perhaps corrected through alternative strategies since no changes to MTC were observed. Conversely, when faced with an obstacle increased toe trajectory effects following sensory perturbations is indicative of a less compensatory ability and emphasis to avoid foot contact. This work is the first to highlight the influence of reduced dorsal foot skin input on locomotor strategies which are commonly encountered in aging populations.
Acknowledgements

I would like to thank my advisory committee Dr. Leah Bent, Dr. Lori Ann Vallis, and Dr. Steve Brown for all of their guidance and support throughout my Master’s degree and for invaluable contributions to this thesis.

First and foremost I would like to express my gratitude to my advisor, Dr. Leah Bent. Thank you so much for all the opportunities I have been provided. I have gained an indispensable skill set over the past two years working in the lab. You always pushed me to strive to do my best work and you have helped me grow and improve as an individual. You are a great mentor and wonderful scientist. To my committee member and unofficial co-advisor, Dr. Lori Ann Vallis – thank you for all of you assistance and support through this entire project. Your infectious positive attitude, passion for research and unwavering willingness to lend a helping hand often lifted my spirits when science was not cooperating and contributed to my passions for pursuit of further research.

To my lab mates and study participants, thank you for allowing me to pursue my research questions, all of your help, laughs and positive encouragement and a huge thank you to Adam Toth, for being my co-pilot in testing, my sound board, my editor and my desk neighbour. I appreciate all that you do. You are all wondering people doing great science.

Kurtis and Andrea, who have had to live with me while writing my working on this Thesis, thank you for your continuing love and tolerance with me on my not so great days and always listening to me babble about science. I could always rely on both of you to put a smile on my face or make me laugh until my stomach hurt. Lastly, Mom and Dad, you have always been so supportive throughout my life and all of my endeavours. I am grateful to have parents like you.
# TABLE OF CONTENTS

Abstract.................................................................................................................................ii
Acknowledgments.....................................................................................................................iii
Table of Contents.....................................................................................................................iv
List of Tables..................................................................................................................................vii
List of Figures..............................................................................................................................viii
List of Abbreviations...................................................................................................................x

Chapter 1: Introduction and Literature Review..............................................................................1
  1.1. PROPRIOCEPTION..............................................................................................................1
  1.2. CUTANEOUS RECEPTORS..........................................................................................3
      1.2.1. Physical Properties of Receptor Endings and Afferents........................................3
      1.2.2. Classification of Mechanoreceptors......................................................................5
          1.2.2.1. Hairy versus Glabrous skin...........................................................................5
          1.2.2.2. Adaptive properties......................................................................................6
          1.2.2.3. Features of receptive fields and locations of receptor endings.....................7
          1.2.2.4. Firing responses of mechanoreceptors.........................................................8
      1.2.3. Functions of Cutaneous Mechanoreceptors.........................................................9
          1.2.3.1. Exteroception – interaction with the environment..........................................9
          1.2.3.2. Proprioception – movement detection.........................................................11
      1.2.4. Cutaneous Receptors Role in Proprioception.......................................................11
          1.2.4.1. Static & Dynamic Sensitivity......................................................................12
          1.2.4.2. Directional Sensitivity...............................................................................13
          1.2.4.3. Task Dependency.........................................................................................13
          1.2.4.4. Anesthesia as a Reliable Interference to Proprioception.............................14
  1.3. LOCOMOTION & ADAPTIVE GAIT..............................................................................16
      1.3.1. Lower limb mechanics in Level Walking............................................................16
      1.3.2. Mechanisms of Adaptive Gait............................................................................18
          1.3.2.1. Obstacle Characteristics.............................................................................19
          1.3.2.2. Differences in Lead and Trail Limb.............................................................20
      1.3.3. Locomotor Reflex Pathways................................................................................22
          1.3.3.1. Evidence in cats of a cutaneous role in gait................................................23
          1.3.3.2. Evidence in Humans of a cutaneous role in gait..........................................24
      1.3.4. The necessity of sensory feedback in steady state gait.......................................25
      1.3.5. The role of sensory feedback in adaptive gait strategies....................................28
      1.3.6. Gait and deficits in sensory feedback..................................................................30
  1.4. LIMITATIONS OF CURRENT LITERATURE AND UNANSWERED QUESTIONS........32
  1.5. OBJECTIVES OF CURRENT WORK AND HYPOTHESES........................................34
      1.5.1. Experiment I........................................................................................................34
      1.5.2. Experiment II......................................................................................................35
Chapter 2: General Methodology

2.1. ETHICAL APPROVAL
2.2. STUDY PARTICIPANTS
2.3. EXPERIMENTAL PROCEDURE
   2.3.1. Experiment I: Level walking
   2.3.2. Experiment II: Adaptive Gait
   2.3.3. Anesthesia Protocol
   2.3.4. Placebo control group
   2.3.5. Monofilament Testing
2.4. EXPERIMENTAL SET-UP
   2.4.1. Motion Capture
   2.4.2. Obstacle for adaptive gait (Experiment II)
   2.4.3. Goggles and Position cues
2.5. DATA ANALYSIS
   2.5.1. Data Processing
   2.5.2. Dependent Variables
      1.5.2.1. Experiment I
      1.5.2.2. Experiment II
   2.5.3. Statistical Analysis

Chapter 3: Experiment I: The Effects of Dorsal Foot Anesthesia on the Control of the Ankle Joint During Normal Level Walking

3.1. INTRODUCTION
3.2. METHODOLOGY
   3.2.1. Subject Characteristics
   3.2.2. Experimental Procedure
   3.2.3. Experimental Set-up
      1.2.3.1. Reducing Cutaneous Input
      1.2.3.2. Visual Perturbation
   3.2.4. Data Analysis
   3.2.5. Statistics
3.3. RESULTS
3.4. DISCUSSION

Chapter 4: Experiment II: What is the role skin on the dorsal ankle joint during Adaptive Gait for Lead and Trail Limb over an Obstacle?

4.1. INTRODUCTION
4.2. METHODOLOGY
   4.2.1. Subject Characteristics
   4.2.2. Experimental Protocol
   4.2.3. Experimental Set-up
      1.2.3.1. Skin
      1.2.3.2. Vision
      1.2.3.3. Obstacle set up
   4.2.4. Data Analysis
   4.2.5. Statistical Analysis
List of Tables

Table 3.1 Subject Characteristics. WFQ score = Waterloo Footedness Questionnaire. A score of >0 indicates right foot dominance. Obstructed distance expressed as a % of body height indicates the peripheral distance that was obstructed when wearing the goggles.

Table 4.1 Raw Means SD and of Toe Clearance (TC), toe peak, Horizontal toe vector, Time to Peak and Horizontal distance (HDx) for both Lead and Trail limb for each test condition, as well as significant interactions between conditions.

Table 4.2 Raw Means SE of relative Ankle, Knee and Hip Position at the time of Toe Clearance. These values are reported for both the lead and trail limb for each condition. Significant interactions are denoted in superscripts. Ankle dorsiflexion, Knee flexion and hip flexion are represented by positive angular positions.
List of Figures

Figure 2.1 Experimental protocol of the trials collected for experiment I (level) and II (adaptive) for each skin block (No anesthetic & anesthetic). The no anesthetic trials always occurred before the anesthetic trials. The pathway (level & adaptive) and vision (full & partial) conditions were block randomized. Within the adaptive gait trials, subjects crossed the obstacle with either right, anesthetized foot as the leading foot or trailing foot.

Figure 2.2 A) The region of anesthesia application (30cm²) and the 3 normalized sites for monofilament testing. Sites 1, 2, 3 were at 10, 50 and 90 % from the proximal border. B) Monofilament testing at site 2, displaying buckling of nylon filament perpendicular to the skin surface.

Figure 2.3 Superior view of experimental set up of camera banks, obstacle location as well as the start and end cut offs for each trial. The start of each trial began when the pelvis was 1.5 meters in front of the global origin and the end of each trial was 3 meters after. Three full strides were collected for each trial. Each stride was named based on their location with respect to the GCS origin: the stride at origin and two subsequent strides after named N-X, N+1, N+2 respectively. The red line represents the approximate obstacle location for experiment II trials. The positive X and Z axes were assigned as the axis of progression and laterally to the right respectively.

Figure 2.4 Marker positions for motion tracking. A) Rigid body set up on Pelvis, Thighs, Shanks and Feet. B) Close up view of Right rigid body and its relative location to the region of anesthesia. C) Digitized anatomical model adopted from Winter (1991).

Figure 2.5A) Schematic drawing of peripheral vision occluded while wearing the goggles B) Obstacle set up with vertical position cues.

Figure 2.6 Interactive V3D model and toe and heel displacement graphs (y axis) utilized to aid in determining TO and HS using the methods described by Zeni et al (2008).

Figure 2.7 On the left is an interactive V3D model illustrating a left heel strike after crossing over the obstacle. On the right are vertical heel displacements for the left (A) and right (C) heel markers. Graph B and D (left and right respectively) illustrate the relative signal between the pelvis and heel utilized in determining HS using the methods described by Zeni et al (2008). Yellow and red ticks represent left and right HS events respectively. Graph B illustrates the common variance in signal in the crossing stride that was manually adjusted.

Figure 2.8 Schematic of the limb position through the mid swing of level gait and the dependent variables. Toe trajectory is represented by dotted limb and MTC, illustrated here is the local minimum of the vertical toe displacement through swing phase. At the point in the gait cycle, the MTC displacement (1), the relative ankle (2A), knee (2K) and hip (3H) angles and lastly the horizontal toe velocity (3) were extracted.

Figure 2.9 Dependent variables for the Adaptive Gait trials. Numbers indicate dependent variables in the crossing stride for both leading (A) and trailing (B) limb over the obstacle. The red box represents the obstacle; the dotted line shows a sample trajectory of the toe marker. Dependent variables correspond to the following: Toe clearance (1), Toe Peak (2), toe vector (3), Relative ankle (4A), knee (4K) and hip (4H) angular positions while the toe is above the obstacle, take off distance (5) and lastly the time to peak (6) were extracted. Leading limb trajectory (A) is demonstrating a negative toe vector with the peak occurring before the obstacle. Trailing limb toe trajectory (B) is demonstrating a positive toe vector with the peak occurring after the obstacle (greater risk of toe contact with obstacle).
Figure 3.1 Log PST from monofilaments means and SE (grams) of the three test sites (10, 50, and 90% from the proximal border) on the dorsal foot before EMLA cream application (Pre Anesthetic) and after (Post Anesthetic). Horizontal dotted line represents the target threshold. Raw mean values of each site are above their respective bars. Asterisks (*) denotes statistical significance. Anesthetic significantly increased PST (p<0.0001) over the whole area of interest.

Figure 3.2 The means and standard errors for A) minimal toe clearance (MTC) and B) horizontal velocity of the toe at MTC (vMTCx) for control (no anesthetic, full vision) and each test condition: PV (no anesthetic, partial vision), anesthetic (anesthetic, full vision) and paired (anesthetic, partial vision). No Anesthetic (light gray bars), Anesthetic (dark gray bars). An * denotes significance from control (No Anesthetic FV) † denotes significance between the bars.

Figure 3.3 Means and standard errors for the four conditions; full vision (FV), partial vision (PV; with goggles), No Anesthetic (light gray bars), Anesthetic (dark gray bars) An * denotes significance from control (No Anesthetic FV), and † denotes significance between the indicated bars for the three dependent variables A) Ankle B) Knee and C) Hip at MTC. Position angles indicate ankle dorsiflexion, knee and hip flexion respectively.

Figure 3.4 The change from control condition of the ankle, knee and hip joint position for each test condition; partial vision, anesthetic, or paired (partial vision and anesthetic). The independent sum represents the mathematical sum of the partial vision and anesthetic experimental test condition changes for each joint. Positive angles indicate ankle dorsiflexion, knee flexion and hip flexion. Asterisks (*) denote significant difference from control. A one-paired t-test used to compare the difference for the ankle, knee and hip changes from control between paired and independent sum revealed no statistical differences between the two groups (p>0.1).

Figure 4.1 Average and standard error for the horizontal take off distance (HDx), toe clearance (TC), toe Peak and time to Peak in the for the leading limb. White bars represent No Anesthetic and Dark bars represent Anesthetic trials. * signifies significance from Control (No Anesthetic, FV). Lines over the bars indicate significance between conditions.

Figure 4.2 Representative data of the sagittal plane (x, y) toe trajectory of the leading toe over the obstacle for control (solid black), PV, (solid gray), Anesthetic (dotted gray) and Paired (dotted black) trails. Crossing stride shown for toe-off before the obstacle until the subsequent toe-off.

Figure 4.3 Average and standard error for the horizontal take off distance(HDx), toe clearance (TC), toe Peak and time to Peak in the for the leading limb. White bars represent No Anesthetic and Dark bars represent Anesthetic trials. * signifies significance from Control (No Anesthetic, FV). Lines over the bars indicate significance between conditions.

Figure 4.4 Representative data of the sagittal plane (x, y) toe trajectory of the trailing toe over the obstacle for control (solid black), PV, (solid gray), Anesthetic (dotted gray) and Paired (dotted black) trails. Crossing stride shown for toe-off before the obstacle until the subsequent toe-off.

Figure 4.5 Mean (SE) for the Ankle (top), knee (middle), and hip (bottom) positions at the time of toe clearance for both the Leading limb. * denotes significance from control trials (No Anesthetic, Full vision). Lines denote significance between conditions. Significance is p<0.05.

Figure 4.6 Mean (SE) for the Ankle (top), knee (middle), and hip (bottom) positions at the time of toe clearance for both the trailing limb. * denotes significance from control trials (No Anesthetic, Full vision). Lines denote significance between conditions. Significance is p<0.05.
List of Abbreviations

AnkleMTC: angular position of the ankle at the time of minimal toe clearance
FA: Fast-adapting
   FA I: Fast adapting, type I
   FA II: Fast adapting type II
GCS: global coordinate system
HDx: horizontal take-off distance
HipMTC: angular position of the hip at the time of minimal toe clearance
HS: heel strike
KneeMTC: angular position of the knee at the time of minimal toe clearance
LCS: local coordinate system
MTC: Minimal Toe Clearance
SA: Slowly adapting
   SA I: Slowly adapting type I
   SA II: Slowly adapting type II
TC: toe clearance
ToePEAK: maximum vertical trajectory of the toe during the obstacle crossing stride
TO: toe off
VMTCx: horizontal velocity of the toe at the time of minimal toe clearance
Chapter 1 – Introduction and Literature Review

1.1 Proprioception

Proprioception, first coined by Bastian (1888) is described as an ability to detect the orientation and movement of one’s own limbs and encompasses both conscious and unconscious movements (Collins & Prochazka 1996). The term has often been interchanged with kinesthesia which specifically encodes for the movement sense, however for this thesis, the term proprioception will be used to include both movement and position sense unless otherwise stated. This ability to detect movements, independent of visual input, is vital for the control and precision of motor tasks (Goodwin et al 1972; Moberg 1983; Edin 1992; Collins et al 2005). Proprioception has a distinguishable quality over vision or vestibular feedback because it integrates input from receptors located in several different tissues such as muscles, tendons, joint capsules and skin. Although a redundancy exists within the system, each receptor type offers unique information and has been shown to exhibit task dependent sensitivities (Goodwin et al 1972; Clark et al 1979; Zehr et al 1997). In the early literature, both joint receptors and muscle spindles were portrayed as the primary contributors to proprioception; the influence of cutaneous receptors was undermined and not even considered for many years (Sherrington 1900; Goodwin et al 1972; Clark et al 1979). Burke and colleagues in 1988 were the first to discredit a principle role of joint receptors in proprioception when they reported a lack of afferent firing activity during joint movements. Their work also provided evidence for a previously proposed idea that joint receptors respond primarily at the extreme ranges of motion in a joint (Burgess & Clark 1969). Notably, they claimed that the role of the joint receptor population for proprioception cannot be ignored entirely; evidence of impairment in movement detection, although modest, was significant following anesthesia of the articulating joint capsule in the knee (Clark et al 1989).
Muscle spindles undoubtedly contribute to proprioception by providing information regarding the length and rate of change of muscle length encompassing both static and dynamic information (Roll & Vedel 1982; Bergenheim 2000). Their involvement has been established using tendon vibration to evoke illusions of muscle lengthening (Burke et al 1976; Roll et al 1989) in both cats (Bessou & Leporte 1962; Proske 1993) and humans (Goodwin et al 1972; Roll & Vedel 1982; Cordo et al 1995). Cordo and colleagues (1995) showed that the primary muscles of the elbow, during a passive throw-like motion could accurately distinguish angular displacements within 1° but when confronted with muscle vibration, target angles were underestimated by roughly 6°. Collins & colleagues (1996; 2005) performed spindle vibration testing in conjunction with cutaneous electrical stimulations and stretch; although they did not dispute the contribution of skin to joint movement perception, the findings from their work lead them to reason that spindles play a superior role in proprioception over skin. Importantly, the integration of both modalities only supplements the acuity of the task.

Clinical observations from reconstructive surgery sparked consideration for the role of cutaneous receptors in humans; once it was reported that efficacy of movement perception was highly contingent on the degree of preserved skin innervation (Moberg 1983). Earlier experiments also indirectly suggested skin as a potential source of proprioception to explain the lack of substantial observed changes following muscle and joint sensory interventions (Gandevia & McCloskey 1976; Burke et al 1988). Subsequent microneurography studies revealed single afferent activation from skin stretches in the hand (Edin 1992), knee (Edin 2004) and lower leg (Aimonetti et al 2007) likely attributing to a proprioceptive function. Although the literature strongly supports spindles as the primary source for providing proprioceptive information, Edin & Johansson (1995) lent credence to the importance of skin’s ability to perceive joint movements
but also challenged spindle dominance by examining the congruency of sensory input from coinciding muscle spindles and skin receptors. Researchers flexed the proximal inter-phalangeal joints, thereby stretching spindles within the extensor digitorum muscles while artificially imitating skin strain patterns associated with extension of the joint. This generated conflicting sensory messages to the brain. Nonetheless, subjects consistently perceived the movement supported by skin strain patterns even with spindle input relaying opposing information. This pivotal work suggests a potentially greater weighting of cutaneous afferent input for movement detection, at least in the finger joint.

Even though aspects of proprioceptive input can be retained from muscles spindles, joint receptors and skin receptors altogether, this thesis will to look to increase the understanding of the contributions and roles of cutaneous mechanoreceptors. The following literature is devoted to cutaneous receptor anatomy, receptor properties, and contributions to proprioception. Furthermore, the use of proprioceptive information in locomotion and adaptive gait will be briefly discussed.

1.2 Cutaneous Receptors

1.2.1 Physical Properties of Receptor Endings and Afferents

Single nerve afferent recordings from microneurography have established the existence of four types of mechanoreceptor afferents within human glabrous skin that respond to low-threshold skin deformations in the form of touch, pressure, stretch and vibration (see Macefield 2005). These mechanoreceptors are innervated by type A, myelinated afferent nerve fibers and each receptor corresponds to their own unique receptor ending. Each receptor ending also responds preferentially to specific stimuli which serve as an additional method of categorizing
afferents. In addition to these four mechanoreceptor afferents, hairy skin includes a hair unit afferent that is extremely sensitive to the movements of individual hair follicles (Iggo 1977; Edin 2001; Mahns 2006).

Mechanoreceptors are commonly classified based on their adaptability (i.e. how quickly they adapt to a stimulus) or their type (i.e. nature of receptive field). Skin receptors can be classified as either slowly adapting (SA) or fast adapting (FA) based on their response to contact and constant indentation, and further differentiated as type I or type II receptors based on a small or large receptive field, respectively. Each of these units is sensitive to distinct types of mechanical stimuli and respond with unique discharge patterns. Although these unit characteristics were initially summarized in animal species, Looft (1986) found parallel properties of the receptors in human skin.

Each mechanoreceptor has a unique receptor ending that can be recognized by its morphology. These have been identified as Merkel discs, Ruffini endings, Meissner corpuscles, and Pacinian corpuscles. Their identifiable features have been described predominantly from biopsies in anesthetized cats (Iggo & Muir 1969; Chambers et al 1972; Iggo Ogawa 1977) but samples from glabrous skin corroborated structural similarities for Ruffini endings in humans (Hatala & Munger 1981). No other literature has specifically examined the morphology of other receptor endings in human biopsies; however associations have been made by linking their functional properties with those found in cats through electrophysiological studies (Knibestöl & Vallbo 1970; Vallbo & Johansson 1984; Edin & Abbs 1991; Vallbo et al 1995). Thermoreceptors, nociceptors, and free nerve endings correspond to sensations of temperature and pain, thus will not be addressed in this thesis work.
Merkel discs, innervated by SAI afferents, are located in the epidermal layer of the skin, connected to the papillary folds of the basal layer and individually supplied by separate axons (Iggo & Muir 1969). SAI afferents are believed to innervate Ruffini endings located deep within the dermal layer of the skin, encapsulated with a lamina sheath and filled with fluid (Chambers et al 1972). Their alignment with the collagen fibers likely gives rise to their sensitivity to skin stretch. FAI afferents likely innervate Meissner corpuscles, and similar to Merkel discs can be primarily found lying within the papillary ridges of the epidermal base layer, enveloped in a capsule with thin sheet terminals that are intertwined with lamina cells (Iggo & Ogawa 1977). Lastly, the Pacinian corpuscle is innervated by FAII nerve afferents and extends as the terminal ending and is surrounded by many adjoining layers of lamellae and can be found deep within the dermis and even subcutaneous tissue (Iggo & Ogawa 1977). Hairy skin includes these mechanoreceptors in addition to hair follicle units which have been found to be innervated by countless axon branches, attributing to their tremendous sensitivity (Iggo 1977).

1.2.2 Classification of Mechanoreceptors

1.2.1.1 Hairy versus Glabrous skin

In humans, skin can be classified as either glabrous or hairy. Glabrous skin is found on the palms of the hands and the soles of the feet whereas hairy skin encompasses the remaining skin covering the limbs and trunk. The skin on the face is given its own consideration because of the direct innervation it receives from the fifth cranial nerve (Vallbo et al 1995). Glabrous and hairy skin share similar features including mechanoreceptor populations, but while glabrous skin only contains the four mechanoreceptors, hairy skin also possesses a third fast adapting receptor (FA III), innervating individual hair follicles (Iggo 1977). Edin (2004) also described a third type
of SA receptor from microneurography in the leg that could not be segregated as either a type I or II since it possessed activation qualities of both and named this a SAIII receptor. Previous research conducted by Burgess, Jarvileheto and colleagues (1968; 1981) had identified a similar receptor type. Furthermore, distributions of skin receptors between types and regions of skin differ. Type I receptors are found to be more densely populated in the glabrous skin of the finger tips compared to the palms to aid in tactile sensitivity (Vallbo & Johansson 1979) whereas in the sole of the feet there seems to be an more even distribution of all receptor types with an overall higher prevalence of FA I afferents. This distribution suggests to reflect a role of FA I afferents in balance and postural control (Kennedy & Inglis 2002). In hairy skin, Edin & Abbs (1991) reported a greater grouping of FAI receptors immediately surrounding the dorsal joints in the fingers but a more uniform distribution of SA receptors throughout the dorsal hand surface. In addition, microneurography studies have highlighted a greater proportion of SA receptors in hairy skin (Jarvileheto et al 1981; Vallbo et al 1995). This greater prevalence is believed to be because SA input has a more extensive role in proprioception through deformations of skin overlaying a joint (Edin 1992). For these reasons, the following sections will focus on literature pertaining to cutaneous receptor classification and firing properties in hairy skin due to its proprioceptive nature. However, extensive reviews are available for glabrous skin from authors such as Vallbo & Johansson (1984) as well as Macefield (1998; 2005).

1.2.2.2 Adaptive properties

Mechanoreceptors can be classified based on how they adapt to a stimulus such as a mechanical disturbance of the skin. If a unit responds for the duration of the stimulus with changes in discharge frequency depending on changes in static pressure it is classified as a slowly adapting (SA) receptor (Chambers et al 1972). Conversely, fast adapting (FA) receptors
will only fire during introduction or removal of a stimulus, providing information about contact, velocity and acceleration (Burgess et al 1968; Macefield 2005). Both SA and FA receptors illustrate dynamic sensitivity at the onset of a ramp and hold skin indentation, but once the stimulus becomes static, FA afferents will cease to fire while the SA afferents remain active for the remainder of the stimulus (Chambers et al 1972, Iggo & Muir 1977; Edin & Abbs 1991). At the release of skin indentation, the FA afferent will also transmit a high frequency discharge pattern as an “off” response (Iggo Ogawa 1977). This has been thought to result from the high sensitivity to vibrations in Pacinian corpuscles, characterized by an exponential increase in discharge frequency. Hair follicles innervated by FA afferents respond similarly to Meissner and Pacinian corpuscles since they only discharge during the initial displacement of the hair and also when it returns to its original position. Further to that, the FA discharge frequency is related to the velocity of displacement of the follicle (Brown & Iggo 1967). The majority of these data were collected from feline specimens but Knibestöl & Valbo (1970) found these characteristics to extend to humans.

1.2.2.3 Features of receptive fields and locations of receptor endings

A secondary classification of cutaneous mechanoreceptors pertains to their location within the skin and the nature of their receptive fields. Type I receptors (Merkels & Meissner) have small, oval shaped receptive fields with very sharply defined borders and exhibit relatively uniform sensitivity (Iggo & Muir 1969; Vallbo et al 1995). Moreover, these receptors are located more superficially in the skin within the epidermal layer (Talbot et al 1968; Vallbo et al 1995). On the other hand, type II receptors (Ruffini & Pacinian) tend to be found deeper within the skin near the dermal layer and consequently have larger, more obscure bordered receptive fields with a single zone of maximal sensitivity (Vallbo et al 1995). Chambers et al (1972) speculated that
these receptor endings are more loosely connected to the dermal layers, hence type II afferents can be activated by stimuli at a greater distance from indentation and tend to have a small area within its activation field that is more sensitive. In addition, researchers have reported that the hair unit typically has a large irregular-shaped receptive field with numerous hot spots correlating to individual hair follicles (Iggo 1977). These general classifications described above contain commonalities among firing responses however, each independent afferent responds to a mechanical stimulus that is unique to each receptor ending.

1.2.2.4 Firing responses of mechanoreceptors

Adaptability (SA or FA) and type (type I or II) convey the basic firing responses to skin deformations but subtle differences persist between each individual receptor ending. Slowly adapting receptors (Merkel discs & Ruffini endings) will have a discharge frequency for the duration of the skin deformation to convey static input. SA receptors also display dynamic sensitivity conveyed by a spike in discharge frequency at the onset of mechanical stimuli. During a sustained indentation however, the Merkel discs have an irregular firing pattern (Iggo & Muir 1969) while Ruffini endings illustrate a regular discharge output (Chambers et al 1972).

Microneurography has been able to delineate threshold sensitivities and more detailed firing responses from both tactile stimulations and external vibration frequencies. Fast adapting receptors (Meissner & Pacinian corpuscles) will code for velocity and acceleration of a mechanical force. In particular, Meissner corpuscles (FA I) will code for the rate of skin indentation and contact responses (on/off) and as a result code for edge sensitivity during object recognition but are also particularly sensitive to delicate stroking across the skin. They are activated by frequencies between 8 and 64 Hz (Macefield 1998), but optimally between 30-40Hz (Talbot et al 1968). Pacinian corpuscles, however, exhibit exceptional sensitivity to high
frequencies (up to 400 Hz) and optimally code for accelerations of indentations at 250Hz (Johansson et al 1982). These receptors can be activated by blowing over the skin and/or transient vibrations through held objects, such as a cane used by the blind (Macefield 2005).

Merkel discs, like Meissner corpuscles, are highly sensitive to the rate of indentation and hence have an edge sensitive nature for object recognition. Ruffini endings are very sensitive to stretch and because of its orientation parallel to collagen fibers, SA II responds more robustly when stretched along its axis as opposed to perpendicularly. Due to their deeper locations within the dermis and loose connection with the surrounding tissue, these receptors can also be excited by remote stretches beyond their receptive field. Vibration testing has determined SA afferents to respond to a wide range of frequencies (0.5-400 Hz) and inconsistent findings within the literature for clear cut thresholds for each but both SA I and SA II have maximal sensitivity at the lower range with the greatest response between 0.5-15 Hz (Iggo & Ogawa 1977; Macefield 1998; Toma & Nakajima 1995). Experiments that have determined distinguishable characteristics for each of these receptor types have built the foundation to probe the functional uses of each of these receptor endings and been used extensively in subsequent research. This work aims to provide further understanding of the functional relevance of the collaboration of these cutaneous mechanoreceptors for joint position sense during an active and complex task of human locomotion.

1.2.3 Functions of Cutaneous Mechanoreceptors

1.2.3.1 Exteroception – interaction with the environment

The glabrous skin of the hands and feet has been studied extensively since these surfaces are commonly used to interact with our environment. Early work distinguished the unique functional roles for each receptor ending to provide tactile information in humans (Vallbo &
Johansson 1984). The densely and overlapping receptive fields of FA units in the fingertips (Johansson & Vallbo 1979; Vallbo & Johansson 1984) presumably are utilized to perceive textures, shapes and ridges to facilitate object recognition (Goodwin et al 1997; Levy et al 2007).

Exteroceptive feedback is also obtained from the skin on the soles of the feet and is thought to play an important role during balance and postural control. These hypotheses have been addressed using methods that reduced sensory feedback on the plantar surface via ice cooling, anesthesia and ischemia (Horak & Nashner 1990; Nurse & Nigg 2001; Meyer et al 2004). Despite the manner of sensory reduction; with impaired cutaneous feedback, there are marked increases in sway characterized by greater deviations in center of pressure (COP) (Horak & Nashner 1990; Meyer et al 2004). Work from Perry and coworkers (2001) also found detriments in gait termination characteristics following foot cooling. During gait, skin on the plantar surface of the foot provides similar tactile feedback regarding pressure distribution to aid in balance and when removed through icing alters gait mechanics (Nurse & Nigg 2001).

However, cooling of the foot sole is also capable of changing the kinematics of the ankle, knee and hip during gait (Eils et al 2004). Particularly, changes were more pronounced at the end of stance phase as the foot transitions into swing and were interpreted as a more cautious strategy, implemented to decrease acceleration forces in push-off. Whether performing a static or dynamic task, there is significant evidence that feedback from cutaneous receptors on the soles of the feet is important, and ultimately leads to the alteration of activation patterns in lower limb muscles to conserve balance (Nurse & Nigg 2001; Meyer et al 2004; Eils et al 2004). This information is of particular interest when considering the increasing incidence of diabetic neuropathy in our society and that these individuals have shown substantial decreases in stability and postural control in gait (Cavanagh et al 1992). Similar detriments exist within elderly populations, who
have elevated cutaneous stimulus thresholds. It is speculated that these increased thresholds are one of the main factors leading to higher incidence of falls in this population (Inglis et al 2002).

The tactile input from skin when interacting with surfaces and objects in our environment is undeniably fundamental for spatial resolution, object recognition and balance, but the hairy skin surrounding our joints presumably also serves another important function: to assist in movement perception and control.

1.2.3.2 Proprioception – movement detection

Accumulating evidence strongly supports the involvement of cutaneous receptors for the detection and evaluation of positions and movements about joints. Microneurography provides evidence that cutaneous receptors in the hairy skin respond to movements of the fingers (Edin & Abbs 1991; Edin 1992), knee (Edin 2004) and ankle (Aimonetti et al 2007). Psychophysical studies draw connections between the active firing patterns of these cutaneous receptors with the conscious perception to distinguish movements (Cordo et al 1994; Collins et al 2005; Lowrey et al 2010). Evidence of skin’s role in proprioception is discussed in greater detail below.

1.2.4 Cutaneous Receptors Role in Proprioception

Evidence of cutaneous mechanoreceptor activity following mechanical stimulations was obtained using microneurography experimental protocols but it wasn’t until the assimilation with psychophysical tests and neuroimaging techniques researchers could confirm that the CNS makes use of this proprioceptive input (Cohen et al 1994; Nelson et al 2004). Activations of cortical neurones in primates responded to skin stretch to represent position and movements of limbs (Cohen et al 1994). Additionally, psychophysical tests confirmed use of proprioceptive input in humans following changes in movement perception with sensory manipulations to alter
Since SA II receptors are exceptionally sensitive to stretch (Knibestöl & Valbo 1970; Chambers et al 1972; Edin & Abbs 1991), they are likely the primary supplier to skin’s proprioceptive ability. Specifically, mechanoreceptors whose receptive fields overlay joints or are in remote proximity are of particular importance in joint movement detection (Edin 1992). Moreover, since receptor sensitivity thresholds in hairy skin are lower than in glabrous skin (Macefield 2005), hairy skin can more readily detect skin deformations and thus movements. Of the existing research, the role of skin surrounding the finger joints has been the most extensively studied and well established. Dorsal skin on the hand has greater activation during finger flexion above extension (Edin & Abbs 1991) and Collins & Prochazka (1996) showed skin also plays an important function when identifying which digit is moving. Moreover, when probing the roles of skin, the finger joint has the greatest discrimination of movement if the experimental stimulation uses asymmetrical strain patterns on both the dorsal and ventral aspects of the digit together (Edin & Johansson 1995; Collins et al 2005). Taken together these findings have built the foundation of evidence in support of cutaneous inputs being utilized by the CNS for proprioception of limbs but also that activation traits contain functional relevance and offer a diverse range of movement characteristics.

1.2.4.1 Static & Dynamic Sensitivity

SA units in hairy skin have demonstrated a high fidelity in static (Edin 1992) and dynamic strain patterns (Edin 2004). When external skin stretches were manually applied at different magnitudes, the firing frequency of these afferents increased as a function of the magnitude of indentation (Edin 1992). Furthermore, the mean discharge frequency was positively correlated to the increase of indentation velocity (Edin 2004). Edin & Abbs (1991)
reported an evident static and dynamic response of SA receptors during the onset of a skin deformation while FA receptors mainly illustrated dynamic. Additionally, SA receptors (I and II) could be activated by stretches of remote skin regions whereas FA I receptors were only active when a unit was close to or overlaying the moving joint. Ultimately, the ability for cutaneous receptors to encode for joint positions based on sustained indentation during skin stretches as well as dynamic movement characteristics is evident from these experiments.

1.2.4.2 Directional Sensitivity

In addition to providing information about the magnitudes of stimulation and rate of applied stimulus, skin units have demonstrated a directional sensitivity through a higher discharge frequency when stretched in a specific direction. Chambers and colleagues (1972) used microneurography in cats to provide evidence that SA II receptors respond with a higher discharge frequency if the skin is stretched in one axis along the receptive field over any other axis. This was corroborated on the dorsal skin of human finger joints with afferents showing preferential firing to finger flexion (Edin 1992) and more recently in the lower leg to ankle plantarflexion more so than any other direction (Aimonetti et al 2007). With the accumulating research, there is certainty that skin receptors are pertinent in movement and position sense; however the specific use of skin receptors during different tasks remains to be elucidated.

1.2.4.3 Task Dependency

The directional firing sensitivities of cutaneous afferents distinguish greater details of a movement task and led researchers to believe that skin can possibly discern task dependency. Microneurography and electrophysiology tests are incredibly valuable to isolate the firing responses and sensitivities to different mechanical stimuli, but the majority of these studies are limited to evoke the illusion of movement without imposing any actual movements about a joint.
Thus, these fail to accurately imitate the asymmetrical skin strain patterns evoked during true movement (Edin & Johansson 1995). As a result, researchers began to investigate skin input during passive movements (Edin & Johansson 1995; Simoneau 1997; Aimonetti et al 2007; Lowrey et al 2010). For these motions, strain patterns evoked would be authentic but would also isolate skin receptor contributions from descending CNS input (Smith et al 2009), as well as from the gamma motor drive responsible for spindle sensitivity associated with muscle activations. However, Bergenheim (2000) examined the proprioceptive population coding for two-dimensional limb movement and revealed that muscle spindles contribute to kinethesis by integrating length and rate of input and they remain active regardless of active, passive, or isometric movements. This compels a line of questioning as to whether passive movements are in fact isolating the input from cutaneous receptors and if they are not then what is the advantage of passive movements over functionally active tasks? An active task can probe the use of a sensory modality by manipulating its input but also grant functional purpose and importance. In addition, active tasks expose the importance of this sensory feedback in light of descending input from the CNS as well as interactions with other sensory inputs. Collins and colleagues (1996; 2005) reported greater acuity of movement detection when both skin and muscle input could be integrated compared to each alone.

1.2.4.4 Anesthesia as a Reliable Interference with Proprioception

Different experiments have used a variety of different methods to directly explore the involvement of cutaneous mechanoreceptors in movement perception tasks; electrical stimulation (Collins & Prochaska 1996; Zehr et al 1997), stretch (Edin 1992, Edin 2004, Collins et a 2000, Collins et a 2005), vibration (Inglis et al 2002); anesthesia (Clark et al 1979; Moberg 1983), ischemia (Inui et al 2012), and ice (Hopper et al 1997). Notably, it is difficult to isolate
the involvement of cutaneous receptor populations during a dynamic task such as locomotion without disturbing the underlying muscles or evoking withdrawal reflexes. While vibration is an effective tool to assess skin contribution in the foot sole (Kavounoundias et al 1999; Inglis et al 2002), vibration of the dorsal ankle joint during locomotion would prove difficult because of the dynamic nature of the task, and additionally would likely influence underlying tendons that also are capable of providing sensory feedback. Furthermore, with nerve stimulation there is an uncertainty that receptor endings only in the skin, separate from spindle or joint are being affected. As a caveat, taping of a joint has been used to increase the natural skin strain patterns and has been shown to improve the acuity of ankle proprioception, although changes were not as apparent during a weight bearing task (Simoneau et al 1997).

In addition to skin augmentation, research has also explored the effect of removing skin input to highlight its roles by means of ischemia, ice and anesthesia. Horak & Nashner (1990) explored the sensory information provided by skin by using ischemic hypoxia to reduce blood flow to a downstream area. While allowing researchers to test proprioceptive properties, this experimental paradigm impedes input from all somatosensory afferents (spindles, GTOs, joints and skin). As such, it fails to isolate the proprioceptive contribution of cutaneous receptors alone. Many studies have used ice as an alternative method to reduce skin sensation (Perry et al 2001,McKeon & Hertal 2007, Muise et al. 2012) but when using ice submersion, the potential influence it may have on muscle spindle activation within the underlying muscles must be considered. Recent work (Lowrey et al 2013) has shown that cutaneous receptor activation begins to return after only a few short minutes following the removal of ice and is not recommended during gait tasks where the decrease in cutaneous feedback will not be consistent
throughout testing. Due to the multiple conditions in the current experimental paradigm, ice was deemed an unsuitable method to maintain anesthesia throughout testing.

Topical Anaesthetic was chosen as the optimal method for reducing cutaneous sensation for the following study because of the longevity and stability of its effects. Notably, when anesthetic is applied topically, it cannot penetrate beyond the dermis layer of skin thus muscle spindles and superficial tendons in the ankle are left unaffected (Koppel et al 2000). Therefore, we can be confident that the manipulation of skin input is discrete. Anesthesia has been used in several other studies to examine the effects of diminished skin input. Moberg (1983) found that error of movement perception increased as a function of the anesthetized area. Previous experiments using anesthetic continuously demonstrated an encumbering ability to detect movements and positions in psychophysical testing (Edin & Johansson 1995; Lowrey et al 2010; Cordo et al 2011). The effects of skin loss in passive tasks have highlighted the necessity of skin but the consequence of impaired cutaneous feedback has yet to be considered in a dynamic task such as locomotion. This reduced feedback is of particular importance due to degradations of the sensory systems commonly seen in aging and pathological populations, as well as the concomitant declines in postural control and joint position sense (Verschueren et al 2002b; Kovacs 2005).

1.3 Locomotion & Adaptive Gait

1.3.1 Lower Limb Mechanics in Level Walking

Bipedal locomotion can be described as a cyclical sequence of movements that is highly coordinated and produced by distinct activation patterns of lower limb muscles. The gait cycle is composed of two primary phases: 1) the stance phase (when the foot is in contact with ground, providing support) and, 2) the swing phase (the forward propulsion of the foot, out of contact
with the surface environment). In the stance phase, eccentric contractions of leg muscles provides stability during heel strike but highly patterned muscle activations also create the force and power to propel the body forward and push off from the ground as the foot transitions into swing respectively (Winter 1987). The swing phase has been previously reported as a more passive movement driven by momentum to create a pendular motion, however, Mena et al (1981) demonstrated that although this is seemingly more the case for the thigh and shank segments, the foot requires more active muscular control about the ankle to adequately clear the ground. Furthermore, muscular forces near the end of swing serve to control the foot landing rather than generating limb movements (Patla & Reitdyk 1993).

The control of the limb through the swing phase requires adequate shortening of the distance between the toe and hip to enable successful clearance (Moosebhoy & Gard 2006). Through mid-swing, individuals clear the ground by a mere 1-2 cm (Murray & Clarkson 1966; Winter 1992; Moosebhoy & Gard 2006). Likewise, Winter (1992) reported peak horizontal velocities of the toe at this critical clearance point, maximizing the risk of tripping (Mills & Barrett 2001). Furthermore, Moosebhoy and Gard (2006) recorded kinematic data from healthy level gait and performed a sensitivity analysis to determine how changes in angular positions of the ankle, knee and hip could affect the minimal toe clearance. They reported that changes were most sensitive to the ankle followed by the hip and lastly the knee. Their findings were contradictory to those reported from Winter (1992), who reported that angular changes were most sensitive at the knee, followed by the ankle and hip; changes as small as 1.35° at the knee and roughly 2° at the hip or ankle produces variability of almost 50% in toe clearances. Despite the slight differences in the sensitivity analyses, both studies found that minute changes to the limb positions through swing are capable of generating substantial changes in minimal toe
clearance, suggesting the swing limb requires strict control by the CNS and joint position sense is vital for success of the locomotor task.

Investigations into steady state gait are valuable to gain an understanding of the basic locomotor patterns but rarely do we ambulate through an uncluttered and even terrain environment. Therefore, also having an understanding of the mechanisms to negotiate adaptive gait patterns is essential to grasp the control of human movements.

1.3.2 Mechanisms of Adaptive Gait

It is rare that we locomote through our environment without encountering changes to surface terrain, or obstacles in our path. Introducing these types of perturbations is an excellent way of studying how sensory systems can detect and implement necessary adaptations to the environment. Compared to level walking, walking over an obstacle requires an upward bias of the swing limb and increased joint flexion to ensure successful clearance of the body end point (Patla & Reitdyk 1993; Patla et al 1996). Changes to the joint kinematics are supported by the changes in muscle activity and impulse forces (Patla & Reitdyk 1993). McFadyen & Carnahan (1997) compared the relative joint angles and net joint moments between level unobstructed gait and an obstacle crossing. In the presence of an obstacle, all three relative joint angles are in a greater degree of flexion during early swing but there are only marked increases in the knee and hip flexor moments and minimal changes in ankle moment. It should be noted that this latter study only investigated the effects of an obstacle on the first limb as it crossed over.

These are some of general requirements to avoid an obstacle within the environment, but the control and the trajectory of the limbs over the obstacle is very context dependent. Two major factors that contribute to the strategy of crossing include characteristics about the obstacle
itself and/or whether the limb crossing is the first (lead) or second (trailing) going over. These factors are discussed in more detail below.

1.3.2 Obstacle Characteristics

When an obstacle is presented in the path of locomotion, it requires an adaptive strategy to avoid contact with the obstacle and promote successful crossing. To implement a crossing strategy requires two key pieces of information: one requires the obstacle height and its location (Mohagheghi et al 2004). Toe clearance, clearance variability and swing phase duration increase as a function of height whereas toe velocity and relative joint angles showed the opposite effect (ie: more flexion) (Patla & Reidtyk 1993; Patla et al 1996). On the other hand, the width of an obstacle changes the lower limb kinematic profiles compared to unobstructed gait, but toe trajectories of different widths are very similar (Patla & Riedtyk 1993). When faced with an obstacle in the environment, the decision to go over or around it is scaled to the relationship between the individual’s height and obstacle height (Patla 1997). Obstacles that are roughly half of the subject’s total leg length are more likely to cause the subject to circumvent around than go over, if given a choice. The decision is likely made by evaluating efficiency versus safety (Warren 1988).

Equally important in determining the locomotor adaptive strategy is the obstacle location relative to the phase within the gait cycle (Patla et al 1991). By constraining subjects to step over an unexpected dynamic obstacle (Patla et al 1991) or by occluding the optic flow input at different points as the obstacle approaches (Mohagheghi et al 2004) we can test how gait strategies are executed based on temporal and spatial cues. When given less than one step (<500ms) to adapt the change of surface level, the success rate of clearance decreases as much as 40% for a high obstacle (8 cm) even though early kinematic responses are evident (Patla et al
This suggests that individuals are capable of reacting within the short time frame, but there is simply a time constraint on adequate scaling. When given more than two steps to evaluate the change in surface, individuals can adapt and elicit appropriate scaling responses.

As an alternative to an obstacle that suddenly appears, when vision is manipulated but the obstacle is stationary, declines in success rate are illustrated but only by 10% (Patla 1998). It is possible that obstacle characteristics and approximate locations can be stored in the memory and feed forward visual information is proficient in manifesting adaptive gait strategies. In the same way, if vision is removed in the approach phase (two strides before), strategies revert to optimize safety by increasing clearances and take off distances (Mohagheghi et al 2004). An absence of exproprioceptive information regarding accurate height for appropriate limb elevation and foot placement before the obstacle requires a very cautious strategy to be implemented.

Another interesting factor accounted for when planning an obstacle crossing strategy is the integrity of the obstacle structure. With a fragile versus solid object, intrinsic properties of the obstacle can pose a greater threat to stability if contact is made with a fragile object more so than a solid. When toe trajectories are compared between solid and fragile objects, clearances increased and toe velocities were reduced for the fragile obstacle (Patla et al 1996).

**1.3.2.2 Differences between Lead and Trailing Limb**

In conjunction with characteristics about the obstacle itself, the limb crossing over is controlled differently depending on whether it is the first (leading limb) or second limb over (trailing limb). Several studies have investigated the inter-limb coordination and there is compelling evidence that each limb is controlled independently from one another however each exhibits signs of similar joint coordination (Patla et al 1996; Lu et al 2008; Rhea & Reitdyk 2011). Crossing over an obstacle requires different mechanics for the lead and trail limbs and
these differences are accompanied by differences in muscle activation patterns. The lead limb relies predominantly on knee and hip flexion whereas the trailing limb requires more flexion of the knee and ankle (Patla et al 1996). In addition, the visual availability between each limb is also significantly different. Visual information is available when the leading limb is crossing over, but not for the trailing limb as it is always behind and thus online visual input is not available. For this reason, researchers believe that the lead limb is controlled predominantly with online visual input while the trailing limb must use feed forward visual input as well as online kinesthetic cues to control the limb trajectory (Patla 1998; Mohagheghi et al 2004). Although the lead and trail limbs have similar kinematic demands to scale over an obstacle, they have very different stability demands (Lu et al 2008). As obstacle height increases, the lead limb increases toe clearances accordingly, but the trailing limb clearances remain similar across several obstacle heights (Patla et al 1996). With each limb, there are different inherent stability threats while stepping over an obstacle. As the trail limb crosses over an obstacle, the COM is moving towards the support limb and thus the stability threat is minimized. Conversely, the forward propulsion of the leading limb is pulling the COM to move away from the supporting limb (Patla et al 1991). Therefore, the leading limb contact with an obstacle would have a much smaller likelihood to recover from a trip and as such, imparts greater clearances to ensure no foot contacts are made. Lastly, Mohagheghi and coworkers (2004) investigated the correlations between each limbs’ toe clearance and their respective horizontal take off distances. They found that both lead and trail limb take off distances are linked to the subsequent toe clearances but the correlations for the trailing limb are much stronger than for the leading limb. It appears that, visual cues for foot placement before an obstacle are imperative for successful obstacle crossing.
1.3.3 Locomotor Reflex Pathways

The basic rhythmic pattern of locomotion has been shown to exist within the neuronal networks of the spinal cord known as central pattern generators (CPG) (Kendel et al 2000). These networks have been predominately demonstrated through work in decerebrate cats (Sherrington 1910; Grillner 1973; Forssberg 1979; Rossignol 2006) though they have also been postulated to reside within humans from work with chronic spinal patients whose lack of descending input did not prevent locomotor synergies (Bussel et al 1992; Dimitrijevic et al 1998). However, the patterns of locomotion are not as strictly stereotyped as once believed (Kendel et al 2000). Accumulating evidence advocates that integration from sensory afferents is used to refine the motor task and ultimately help maintain postural control making us proficient when adapting to uneven terrains, scaling over obstacles or alternating foot placements (see Rossignol 2006).

Early work that highlighted the contribution of afferent feedback onto these spinal networks derived from experiments on decerebrate cats (Sherrington 1910). These experiments illustrated the robust control of hip proprioceptors during the limb stance to swing transition, to powerfully prompt a consistent hip flexion and limb withdrawal following hip extension. This was a reversed response regardless of walking direction (forward or backward) providing evidence of task dependency (Grillner & Rossignol 1978) but ceased if hip extension was prevented also illustrating phase dependency (Sherrington 1910). Likewise, the flexibility of locomotor patterns was also exhibited in weight-supported infants on a treadmill (Thelen et al 1987; Yang & Pang 2001) which exposes the existence of inherent rhythmic patterns long before first steps are taken. Since then, further work has illustrated the locomotor-specific roles of skin in both humans and cats. The next sections will focus on the evidence for cutaneous feedback to modulate gait reflex patterns in cat and humans.
1.3.3.1 Evidence in Cats of a cutaneous role in gait

Cutaneous stimulation was shown to evoke robust reflexive patterns, modifying locomotion in decerebrate cats (Forssberg 1975; 1979; Duysens & Pearson 1976; Drew & Rossignol 1978). Since then, research has revealed that these reflexes are highly adaptable and have inherent task dependency (see reviews Pearson et al 1995; Whelen 1996; Rossignol 2006). Specifically, denervation of different cutaneous afferents within the hind limb evoke differing responses according to the phase of the gait cycle as well as the select site of stimulation and the phase in which it is evoked (Forssberg 1975; Duysens & Pearson 1976; Buford & Smith 1993).

Locomotion can be modulated by exteroceptive cutaneous input as well as by intrinsic proprioceptive input to facilitate stability and limb control. Exteroceptive feedback was shown by decerebrate cats that were able to effortlessly adapt their gait speed to match the speed on the treadmill without higher center contribution (Barbeau & Rossignol 1987). When cats walked on a split treadmill travelling at different speeds, they were able to adjust the speed of each limb and coordinate a functional locomotor pattern (Kuligan & Shik 1970; Yanagihara et al 1993; Forssberg et al 1980). Proprioceptive feedback from cutaneous receptors was first illustrated from Forssberg and colleagues (1975) to demonstrate a mechanical withdrawal termed “corrective stumbling response”. Mechanical stimuli on the dorsal hind limb during swing served to coordinate a pattern of limb flexion causing withdrawal from the object, followed by a safe foot placement. These reflexes were confirmed to originate from cutaneous afferents since after local intradermal anesthetic, the response was completely abolished. Later, these same researchers demonstrated that a non painful electrical stimulation on the same region of the hind limb elicited the same limb responses (Forssberg et al 1979).
1.3.3.2 Evidence in Humans of a cutaneous role in gait

In human locomotion reflexes, some work has examined muscle spindle contributions using vibratory stimuli to evoke illusions of muscle lengthening (Ivanenko et al 2000; Sorensen et al 2002; Verschueren et al 2002b). With vibrations on the tendon of biceps femoris during treadmill walking would result in altered gait speed; however vibration of lower limb muscles did not elicit any changes to gait parameters (Ivankenko et al 2000). Vercherueren et al (2002) also used muscle vibration of the tibialis anterior (TA) and triceps surae to investigate intra-limb coordination and found that, although vibrations could elicit changes to individual joints, coordination as a whole was unaffected. Similar to prepared spinal cats, cutaneous reflexes in human locomotion have comparable task and phase dependency (Yang & Stein 1990; Duysens et al 1992; Zehr et al 1997). As initially demonstrated by Forssberg et al (1975; 1979), Zehr and coworkers (1997; 1998) illustrated corrective limb withdrawal responses from stimulation of cutaneous nerve terminals in the lower leg. Superficial peroneal (SP) branches innervate the dorsal surface of the leg and foot and its excitation elicited not only changes to the EMG activity but also kinematic angular modifications to the ankle and knee depending on the phase of gait (Zehr et al 1997). When SP was stimulated during the stance phase of gait, responses in EMG or kinematic activity were minimal, but if electrically stimulated during early swing phase, the cutaneous reflex resulted in a suppression of TA activity and facilitation of ankle plantarflexion. Moreover, early swing phase SP activation also created an increase in biceps femoris muscle activity and increased knee flexion. Conversely, tibial nerve stimulation resulted in more ankle dorsiflexion accompanied by TA facilitation in early swing. These equate to the changes observed in the decerebrate cats (Forssberg et al 1975) to effectively withdraw and swing the limb over the perturbation.
1.3.4 The necessity of sensory feedback in steady state gait

Although basic locomotor rhythms can be generated from neuronal networks within the spinal cord, sensory feedback contains valuable information allowing for precise locomotor control and timing. Sensory feedback is thought to be used during each step (online manner) since regular step patterns are immediately resumed following a perturbation (Zehr & Stein 1999; Pang & Yang 2001; Rossignol 2006). Despite the research on somatosensory contributions in proprioceptive feedback, the role of somatosensory feedback during locomotion from a locomotor planning perspective, is not well understood. On the other hand, visual and vestibular contributions have both been extensively studied and cannot be overlooked when considering the control of locomotion.

Vision has an advantage over both vestibular and somatosensory systems due to its ability to act in a feed forward and online manner giving information about distant and upcoming cues (Patla & Vickers 1997) as well as respond to changes in the instantaneous environment (Patla et al 1991; Hollands & Marple-Horvak 1996). Specifically, vision can provide two types of information: exteroceptive visual cues providing input about the environment (such as characteristics of upcoming surface terrain or obstacles to avoid) and exproprioception providing interactive information regarding the individual relative to the environment (such as distance between the individual and a potential stability hazard) (Rhea & Reitdyk 2006). When visual information is periodically removed during locomotion, minimal changes are observed in target path but with extended periods without vision, individuals will reduce gait speed and error to target is substantially larger (Thomson 1983). Moreover, Patla (1998) demonstrated that visual monitoring about the approaching environment is not continuous but sampled intermittently. This suggests that if individuals are still able to successfully travel through their environment
while visual information is not continuously available, then vision may be important but not vital for successful navigation. This may also suggest that other sensory sources are utilized to assist the control of limb movements and trajectory paths in concert with phasic visual input.

The vestibular system has been shown to contribute to the alignment of the body to a trajectory paths and navigate through the environment (Bent et al 2000; Cohen 2000; Kennedy et al 2003). With bilateral vestibular deficits, individuals are capable of walking along a target path without vision for a short distance but veer off earlier than healthy subjects (Cohen 2000). This same response is observed following artificial stimulation of the vestibular system (Fitzpatrick et al 1999; Bent et al 2000). Interestingly, the role of the vestibular system displays phase dependency (Bent et al 2004). When using galvanic vestibular stimulation (GVS) at varying points in the gait cycle, researchers found the greatest dependence on vestibular feedback occurred during the double support phase of gait. This finding suggested the vestibular system is used in the planning of progressive steps and foot placement. Across these vestibular studies, the concurrent occlusion of vision with the vestibular perturbation magnified the postural response relative to vestibular perturbation alone. Furthermore, with delivery of GVS and concomitant use of prism goggles to elicit a visual deviation, subjects always displaced walking trajectory towards the visual perturbation (Kennedy et al 2003). Together, these findings suggest that the vestibular system is used during locomotion but vision can prevail with a potentially greater influence over the vestibular system.

Somatosensory input is slightly more complex as it integrates information from various sources and at various locations on the body such as muscle spindles, joint receptors and skin. Each of these somatosensory sub modalities has unique activation properties and can offer distinct elements of feedback. Specifically, skin afferents can provide tactile input (Iggo 1977),
information about body sway from the soles of the feet (Kavounoundias et al 1998) as well as proprioception of our joints (Collins et al 2005; Lowrey et al 2010). The role of somatosensory feedback during locomotion has been investigated by studying exteroceptive input from the soles of the feet (Nurse & Nigg 2001; Eils et al 2004) and from vibrations of lower limb muscles; to activate muscle spindles (Ivankenko 2000; Verschueren et al 2002b). Vibrations of the hamstring muscles during treadmill walking generated changes in gait speed, but no changes in inter-segmental coordination (Ivanenko et al 2000). In contrast, TA and soleus muscles vibration generated angular kinematic changes in the ankle during over ground walking but the vibration effects were isolated to the joint vibrated (Verschueren et al 2002b). These findings would suggest that muscle spindles contribute to isolated joint moments and that the involvement of muscle spindle feedback may depend on task context.

With exposure to ice submersion on the plantar surface of the feet, individuals with regional cooling shifted their center of pressure away from iced region (Nurse & Nigg 2001) and with whole foot reductions, subjects decreased impulse forces and muscle activity during push-off and landings (Eils et al 2004). Furthermore, Eils and coworkers (2004) also investigated the effects of foot sole cooling on the joint kinematics and found that aberrant skin feedback on the foot sole produces changes not only to the ankle joint but to the knee and hip as well. It would appear that unreliable feedback from skin on the soles of the feet during gait causes subjects to employ more cautious gait strategies and capitalize on available sensory input to conserve balance. Since muscle spindle vibration only affected the joint being vibrated but skin impedance coordinated changes at several lower limb joints, it is possible that skin has a greater influence in coordinating intra-limb changes than muscle spindles during human locomotion.
1.3.5 The role of sensory feedback in adaptive gait strategies while going over an obstacle

A change in surface terrain requires modifications to locomotor strategies gained through input from sensory systems. This sensory feedback is used to implement plans for choosing a safe walking path, foot placements and successful obstacle avoidance. How the visual and vestibular systems are involved in adaptive locomotion are fairly well studied but somatosensory and more specifically, the cutaneous receptors information has received little attention in the literature to date.

Many researchers argue that we rely heavily on visual information to employ adaptive gait strategies due to its unique ability to “touch objects at a distance” (Patla 1998; Mohagheghi et al 2004; Rietdyk Rhea 2006; Kennedy et al 2003). Vision can also provide online control to distinguish lower limb movements relative to an obstacle (exproprioception; Reitdyk & Rhea 2006). Without the reliance of vision when crossing over obstacles, individuals have the tendency to employ a safer, more conservative strategy by increasing toe clearances, and decreasing walking speeds (Mohagheghi et al 2004; Patla & Grieg 2006), which supports the propensity to use visual information when it is available. Adequate scaling over an obstacle can be accomplished using only feed forward visual information but requires two primary characteristics to plan obstacle avoidance: the height of the obstacle and its location (Mohagheghi et al 2004). The approach phase is considered to encompass two strides before the upcoming obstacle (Mohagheghi et al 2004) and visual information provided about the environment during this phase is sufficient for the prospective control of the swing limb (Patla & Vickers 1997). However, if visual information is unreliable for a distance greater than three steps before the obstacle, the variability of foot trajectory significantly increases and success rates substantially diminish (Patla 1991; 1998). On the other hand, online visual control is incredibly
stringent and robust. Accurate placement of successive steps can be accomplished in the last 100ms of stance before toe off (Hollands & Marple-Horvat 1996). With a sudden appearance of an obstacle, subjects can still successfully adapt locomotor synergies within one step beforehand by producing an overstated hip flexion to optimize safety (Patla et al 1991). Lastly, the same sampled gazing pattern is observed while crossing the obstacle (Patla & Vickers 1997) as reported in level walking (Patla 1998), thereby highlighting the superfluous effects of continuous visual feedback to effectively cross over the obstacle.

Vestibular contributions to the adaptive gait strategies over obstacles have received less attention compared to vision. McFadyen and colleagues (2007) were the first to consider the role of the vestibular system while crossing over an obstacle. Researchers found that there were no differences in toe trajectories, gait speeds or segment rotations when subjects were exposed to GVS, as compared to level walking. Interestingly, occluded vision alone generated increases in toe clearance and decreases in gait speed but when paired with GVS, there were no amplified pathway deviations and toe clearances. Removal of vision presumably increases the reliance of other sensory inputs but McFadyen et al (2007) found that this was not the case for vestibular information since it would appear that there is no upregulation of vestibular influence in adaptive locomotion.

Virtually no effort has been made to consider the role of the somatosensory system in adaptive gait. One of the few existing studies observed center of mass (COM) and center of pressure (COP) changes following muscle vibration of TA and soleus of the stance limb during obstacle avoidance (Sorensen et al 2002). No changes in toe clearances, step lengths or widths were observed as a result of vibrations but significant increases in peak medio-lateral COM accelerations and smaller distances between anterior-posterior COM and COP were found to
suggest these spindle afferents play a role in balance preservation and regulating COM.

Researchers proposed that spindle afferent feedback in the stance limb during adaptive gait provides a more conservative regulation of COM with respect to the supporting foot. Further exploration into the role of muscle spindles in adaptive gait is required to ascertain its context dependent roles. The use of feedback from skin in lower limbs during obstacle crossing has yet to be established in a healthy population. Most of the previous work on proprioceptive feedback has focused on pathological and ageing populations with deteriorated peripheral feedback (Dyck et al 1987; Cavanagh et al 1992)

1.3.6 Gait and deficits in sensory feedback

Probing sensory feedback during motor tasks in healthy populations would provide a greater understanding for the sensory feedback mechanisms used to control movement. Much can be gained from also studying how this feedback contributes to the detriments in stability and movement control in populations with sensory deficits such as neuropathy patients and the elderly. Diabetes mellitus (DM) patients are a primary example of individuals who develop a peripheral neuropathy. Research has provided evidence of increases in cutaneous sensitivity thresholds from mechanical stimuli and vibrations on the soles of the feet (Dyck et al 1987; Nelander et la 2012). Microneurography revealed that these increases in threshold were perhaps due to abnormal firing responses of afferents of all four mechanoreceptor classes when compared to healthy individuals (Mackel 1989). This study also reported no changes in conduction velocity of the nerve afferent itself, and thus postulated that the firing responses are perhaps due to a limitation of the receptors themselves to transmit the signal. These changes in cutaneous mechanoreceptors characteristics result in decreases in stability (Cavanagh et al 1992) and as a consequence increased risks of falls. In 1994, Mueller and coworkers conducted a gait study on
individuals with DM and showed that neuropathy generates insufficient ankle moments resulting in shorter step lengths, decreased push off power, and slower walking speeds. The considerable detriments in stability with neuropathy parallel experimental simulations of reduced plantar skin feedback using anesthesia or ice in healthy individuals (Perry et al 2001; Meyer et al 2004; Eils et al 2004).

The integrity of sensory feedback also declines with age (Winter 1990; Kovacs 2005) and consequently results in an increased rate of falls to over 40% of elderly over the age of 65 (Prudham & Evans, 1981). There are also evident declines of visual acuity (Glasser & Campbel 1998) and vestibular function in the elderly, however, for the purpose of this thesis only the changes in somatosensory input will be discussed. Numerous studies have investigated the morphological changes of somatosensory receptors with age, such as the decreased number and diameter of muscle spindles as a function of age (Kararizou et al 2005). Furthermore, age is associated with decreased number and concentration of cutaneous mechanoreceptors, particularly the fast adapting, Meissner and Pacinian corpuscles (Cauna et al 1958; Bolten et al 1966). Loss of muscle spindle function has been used to explain the related decreases in joint position sense in the ankle (Verschuerun 2002) and knee (Bullock-Saxton et al 2001). Recently joint position sense of the ankle in elderly subjects showed an even greater decreased performance when the joint position detection task was paired with a cognitive task (Boisgontier et al 2012). Similar declines are observed in vibro-tactile sensitivity of skin in the soles of the feet in elderly compared to young adults (Inglis et al 2002); particularly after the age of 70, thresholds increase two-fold (Perry 2006). These decrements of cutaneous feedback are often associated with the considerable changes in locomotion (see review from Kovacs 2005).
With age, there are decreases in gait speed, as well as stride lengths (Winter 1990; Begg & Sparrow 2006). Combined, these gait parameters create an increased time spent in double support recognized as a more conservative locomotor strategy (Kovacs 2005). Interestingly, the average displacement of toe through swing phase, which delineates as the margin of safety, does not change with age (Winter 1990; Mills et al 2008) however demonstrates a greater variability (Mills et al 2008; Barrett et al 2010). This increase in variability suggests deterioration of the lower limb control and could contribute to the increasing prevalence of falls in the elderly. Moreover, Begg and Sparrow (2006) investigated the joint angles at toe off since these set up the toe trajectory in swing phase. They found reduced ranges of motion, especially of the ankle in elderly and postulated that it may compromise sufficient foot elevations through swing. This is in accordance with Lord et al (1996), who reported overall declines in muscle strength with age such that these individuals likely are incapable of generating sufficient push-off forces.

1.4 Limitations of Current Literature and Unanswered Questions

Despite research that demonstrates the significance of cutaneous feedback on joint movement and position detection; literature on the afferent feedback from skin on the dorsal ankle joint remains limited. Aimonetti et al. (2007) utilized microneurography to exhibit directional sensitivity of the afferent discharge when the ankle was passively moved in plantarflexion and eversion. In following, Lowrey and colleagues (2010) revealed that with the elimination of dorsal cutaneous information, detection of joint movement was impaired and the variability of responses was significantly increased. These findings support the idea that skin receptors indeed play an important role during joint movement detections however earlier studies only demonstrated the contributions of skin in a passively controlled task. What remains unknown is whether this same skin is vital during a dynamic and functional task such as
locomotion which is considerably more complex and typically involves the integration of many other sources of sensory input.

Some locomotor studies have investigated the proprioceptive roles of skin via electrical stimulations of the superficial peroneal nerve and elicited modulations of muscular activity as well as angular kinematics of the ankle and knee in the swing limb of gait (Zehr et al 1997). However, it is unknown whether the effects from nerve stimulation is isolated to skin receptors and whether baseline input from skin in this area is necessary during gait; stimulations applied not only amplified feedback, but were also delivered at specific points within the gait cycle to elicit reflex modulations. Lastly, Zehr et al (1997) did not examine the path of toe trajectory to test whether there are detrimental changes in ankle control that perhaps result in declines in safety margins. The toe trajectory is often selected in gait control studies to compare among populations and treatment interventions because it ultimately represents the end point control of the limb (Patla & Reitdyk 1993).

Taken together, these studies suggest that this region of skin may contribute to the control of the ankle joint during the highly dynamic task of locomotion. Additionally, because it is rare to walk through an uncluttered and evenly surfaced terrain, examining the use of skin in adaptive gait strategies has functional value; sensory feedback during an adaptive task, such as crossing over an obstacle will require different dependencies of sensory feedback than level walking. One factor of sensory feedback during gait has remained invariable: feedback from each sensory source appears to be task and phase dependent and each input has locomotor-specific roles (Bent et al 2004; Rossignol 2006; Patla & Greig 2006). For that reason, in the current study each task (level walking and adaptive gait) was treated independently and individual hypotheses were established.
1.5. Objectives & Hypotheses of Current Work

The aim of this research was to gain an understanding of whether the cutaneous receptors on the dorsal surface of the ankle joint play a role in limb control during an active locomotor task. It was our interest to investigate how altered cutaneous feedback would affect level gait (Experiment I) and subsequently observe how or if the role of skin feedback was changed when subjects were faced with an environment that required adaptive gait (Experiment II).

In addition to testing the effects of skin, a visual condition was introduced. The goal was to impose a greater reliance on skin input and increase task complexity through loss of exproprioception of the swing limb. This was accomplished through a subset of trials during which subjects wore obstructive goggles that removed lower visual field input.

1.5.1 Experiment I:

The objective of experiment I was to assess the proprioceptive importance of skin receptors surrounding the dorsal ankle during locomotion and, specifically, how skin influences the control of the ankle joint through swing.

Hypotheses: It was hypothesized that information from the region of skin on the foot dorsum and ankle is important for ankle control during level gait; demonstrated by increased minimal toe clearances, increased ankle dorsiflexion, increased knee flexion and increased hip flexion. It was also hypothesized that toe velocities during the swing phase will decrease.
1.5.2 Experiment II:

Experiment II investigated the importance of cutaneous feedback from the foot dorsum during adaptive gait. The contribution of skin was tested on the lead and trail limb independently. As such, two discrete hypotheses were proposed based on previous work that has suggested that the control of the lead and trial limb are independently affected by changes of incoming sensory input (Patla et al 1996; Mohagheghi et al 2004).

Hypotheses:

1. It is hypothesized that when the lead limb has reduced skin input from the dorsum of the ankle, toe clearances and toe peaks will increase following an increase in dorsiflexion of the ankle and greater magnitudes of hip flexion which are all angular movements which would act to increase toe clearances.

2. It is hypothesized that reduced skin input on the trail foot dorsum will result in an increase in toe clearance and toe peak but, in order to successfully avoid contact with the obstacle, the ankle will be more plantarflexed and the knee more flexed.
Chapter 2- General Methodology

2.1 Ethical Approval

All experimental procedures were approved by the Ethics Review Board at the University of Guelph and complied with the Declaration of Helsinki. All subjects provided informed written consent prior to testing.

2.2 Study Participants

Twelve healthy subjects (Aged 21.9 years (19-25), height 173.2 cm (157.5 -195.8 cm), weight 69.4kg (50-93kg)) participated in the study. None of the subjects reported any neurological or musculoskeletal disorders, and no one had reported lower limb injuries within the last 6 months. Foot dominance was determined using the Waterloo Footedness Questionnaire (Elias et al 1997); only subjects with right foot dominance were selected (see Appendix). Exclusion criteria included allergies to lidocaine or prilocaine, a lower limb injury within the last 6 months, or diabetes.

2.3 Experimental Procedure

Participants performed 80 block randomized walking trials with 1) cutaneous, 2) visual or 3) both systems simultaneously altered. These modifications in sensory input were tested on i) a level walkway (Experiment I) and ii) along a walkway with an obstacle (Experiment II) (Figure 2.1). The use of an obstacle was included to increase the stability challenge during walking. In particular, we wanted to test whether cutaneous information on the foot dorsum is required during level walking to enable successful gait, or whether such input is only necessary during more complex dynamic tasks such as obstacle crossing. In both experiments completed on the same day, subjects were instructed to walk at a self selected pace down a 8 meter runway.
towards an “X” marked on the wall. All trials were initiated from a verbal cue provided by the researchers.

Starting location was unique for each subject and was established at the start of the experiments by the researchers based on a location that consistently had subjects step over an obstacle with the same foot which they were instructed to initiate each trial with. For trials with an obstacle, subjects started with either the left or right foot so that the right, anesthetized limb would step over the obstacle either first (as leading limb) or second (as trailing limb) thus facilitating the investigation into the roles of cutaneous feedback on each limb. Subjects were unaware that the starting location was selected such that whichever foot initiated the trial was the same foot intended to cross the obstacle first to avoid gait alterations associated with targeting but this location remained the same throughout the entire testing session. For trials with a level walkway, participants were instructed to always start with their right foot. For the purposes of our research questions, the different pathways (level or obstructed) were regarded as two separate experiments and analyzed individually. Further description of each Experiment protocol is outlined below.

2.3.1 Experiment I: Level walking

Subjects began each trial with their right (dominant) foot at the same pre-determined start location described above. The first block of 20 trials were completed with full skin sensation intact (no anesthetic), followed by a block of 20 test trials during which subjects had reduced skin sensation on the dorsal ankle (anesthetic). Within each ‘skin’ block (no anesthetic or anesthetic), there was an additional visual condition that either allowed subjects to have full visual feedback (FV) or partial feedback (PV) via goggles that obstructed the lower visual field. A minimum of 10 trials were collected per test condition.
2.3.2 Experiment II: Adapted gait

Similar to Experiment I, there were 40 trials in which the first half were collected with full skin sensation on the foot dorsum (No Anesthetic) followed by test trials whereby the right foot had reduced cutaneous feedback (Anesthetic). Subjects either crossed the obstacle with the affected right limb first (lead) or second (trail). Furthermore, there were two different levels of visual feedback assigned: full visual feedback (FV) or partial visual feedback (PV). This yielded a total of 8 different conditions (skin (2) x vision (2) x foot (2)). The vision conditions were completed in blocks within each skin condition however, all obstacle trials were completely randomized to alternate which foot crossed the obstacle first (left or right). This randomization allowed researchers to determine if anesthesia had a great influence on control of the lead versus trail limb. A minimum of five trials for each condition were collected. During data collection, a dedicated observer was present to ensure that the appropriate foot crossed the obstacle first and that subjects did not stumble or shuffle during the trials. Trials in which subjects stumbled or crossed with the wrong foot were repeated at the end of data collection; this occurred in <5% of trials.

2.3.3 Anesthesia Protocol

To reduce skin sensation, approximately 2.5 g of a topical anaesthetic (EMLA®: 2.5% lidocaine, 2.5% prilocaine) was applied to an area of skin on the right foot around the dorsum of the ankle and foot. The 30cm² rectangular area (5 x 6 cm) was outlined midway between the malleoli on the dorsum of the ankle joint on the right foot (Figure 2.2a). Three sites at 10, 50, and 90 % below the proximal border were tested using monofilaments (Semmes Weinstein, Stoelting, Co, IL, USA) pre and post anesthetisation (see monofilament testing below). The testing area was first shaved with a disposable razor to remove any hair. Hair follicles have
different activation patterns than cutaneous mechanoreceptors and can be stimulated even without any skin contact (Macefield 2005, Mahns 2006). The cream was applied to the test region and covered with a plastic wrap dressing to maximize absorption. The objective of the anesthetic was to reduce skin sensitivity thresholds in subjects to levels similar to diabetic neuropathy patients (Holewski 1988) as indicated by a monofilament force of >10 g (#15). Perceptual thresholds were first assessed prior to application followed by one hour post application and every 15 minutes thereafter until either the target threshold was achieved, or two hours had past. Topical Anaesthetic was chosen as the optimal method for reducing cutaneous sensation for this protocol because of the longevity and stability of its effects. Importantly, when applied topically, anesthetic is not able to penetrate beyond the dermis layer of skin, which leaves muscle spindle and superficial tendons in the ankle unaffected (Koppel et al 2000). Once the anesthetic cream had been applied to the area of the dorsum ankle, weight bearing of the right limb was avoided to minimize the potential for adaptive mechanisms and re-weighting of sensory modalities.

2.4.4 Placebo Control Group

Three separate subjects unknowingly received a non-anaesthetic cream as a placebo to control and assess changes unrelated to the removal of skin input and help ensure no confounding psychological aspect was affecting gait strategies. There was still a minimum hour wait time post cream application, and subjects received the same instruction for trials as test subjects.

2.4.5 Monofilament Testing

To quantify the effect of the anesthesia, perceptual sensitivity thresholds (PST) were determined at three sites pre and post anaesthetic application using Semmes-Weinstein
monofilaments (Stoelting, Co, IL, USA) (Figure 2.2b). PST was defined as the smallest perceived stimulus at a given site. Monofilaments are a clinical tool habitually used to test for peripheral neuropathies. Each nylon filament diameter corresponds to a calibrated buckling force when applied perpendicular to the skin. The monofilaments were calibrated using an analytical scale prior to use to determine the actual force of each filament being applied.

Monofilament thresholds were defined as the lowest perceived stimulation force (g) which was confirmed at least 75% of the time (Diamond et al 1989). With eyes closed, subjects responded with a verbalized “yes/no” and were asked to be 90% confident for an affirmation of a perceived stimulation. The target monofilament #15 was always chosen as the starting monofilament at each site; a 4-2-1 pseudo-staircase method (Dyck et al 1993) was used to determine each subject’s threshold. At each site, at least one catch trial was performed in which no stimulus was given to verify sincerity of results.

2.4 Experimental Set-Up

2.4.1 Motion Capture

To assess 3D motion during locomotor tasks, kinematic data were sampled at 60 Hz and recorded using an opto-electric capture system (OPTOTRAK 3020, Northern Digital, Waterloo, ON). The global coordinate system (GCS) was digitized to align with the International Society of Biomechanics standard – X as the axis of progression, Y as the vertical axis and Z as the medio-lateral axis. Data were collected from three banks of cameras oriented to maximize the camera volume surrounding the obstacle location (Figure 2.3). Before each testing session, the walking space was calibrated using a digitizing cube with factory calibrated locations and a between-camera Root Mean Square (RMS) error of <0.40 mm was accepted for calibration. Each segment was defined using a local coordinate system (LCS) from either three or four non-collinear
infrared markers (IREDS) mounted on rigid body platforms. To capture 3D motion, a minimum of three non-collinear markers are required to represent a segment’s motion; however, if one marker becomes obstructed caused by the movement itself, the segment does not get recorded. For that reason, the thigh and shank rigid bodies included an additional IRED to improve capture rate of these segments during the crossing stride. Before each test session these rigid bodies were each calibrated with a RMS error set to 5 mm. A residual analysis was executed during post-processing to eliminate sections of each trial that exhibited greater than 3 mm of error.

Rigid bodies were securely attached via double sided skin tape to the antero-lateral aspects of the pelvis, thighs, shanks and feet. Anatomical landmarks were digitized with respect to each rigid body to manifest anatomical relevance using a biomechanical model (Winter 1998) (Figure 2.4a). With respect to the probed anatomical locations, the pelvis segment was defined using bilateral anterior superior iliac spines (ASIS) and medial iliac crests. Each thigh segment was defined using the greater trochanter and medial and lateral epicondyles landmarks. The medial and lateral tibial plateau and malleolli were digitized to define the shanks and lastly, the feet were defined using the first and fifth metatarsal, as well as the anterior hallux and posterior heel (Figure 2.4c). To be included into the analysis, all IRED markers must have been visible at least 60% of the trial. Utilizing a rigid body model, markers and their respective digitized points are assume to be fixed in space with respect to one another (Robertson 1996). Therefore, it was crucial that once the anatomical landmarks were digitized that the platform were fastened securely to each segment and did not change location. The platforms were fixed to each segment using double sided skin tape; however the rigid platform of the right foot (foot to be anesthetized for reduced skin sensation) was secured with a skin-adhesive (E-Z bond glue, K&R
International, CA, USA) to avoid extra proprioceptive cues (Figure 2.4b) as taping of joints has been shown to improve the perception of joint movements (Simoneau et al 1997).

2.4.2 Obstacle for adaptive gait (Experiment II)

Prior to data collection, an obstacle height was set to 45% of each subject’s lower leg length (approximately 20.6 cm), which was defined as the distance between the floor and the head of the fibula. Patla (1997) demonstrated that individuals were more likely to go around rather than over obstacles greater than 50% of their leg length in a natural environment. Conversely, the same researchers (Patla, Prentice et al 1991; 1995) have shown that obstacles of low heights (0.5-2 cm) generated minimal changes when compared to normal walking given that the foot clears the ground by approximately 1-2 cm (Winter 1991). Our obstacle height was chosen to increase the probability of seeing a gait modification, while presenting an obstruction relevant to everyday challenges. The obstacle was a wooden dowel suspended by two metal brackets that could easily become dislodged if contacted with the foot. The width of the obstacle was approximately 96 cm, similar to the width of a doorway.

2.4.3 Goggles & Position cues

To increase reliance on somatosensory input, participants wore “basketball goggles” in a subset of walking trials (Figure 2.5a). These goggles obstructed the lower half of the visual field, removing visual information about the individual’s immediate environment (exteroception) as well as information regarding their lower limbs during gait (exproprioception). Subjects had the opportunity to walk while wearing the goggles prior to data collection. This allowed subjects to become familiar walking with reduced visual information. Each individual’s ‘obstructed distance’ was measured to establish the extent of peripheral vision removed via the basketball goggles. To measure the obstructed distance, subjects walked towards a marked target (X)
across the room while the obstacle was in position and were asked to stop as soon as the obstacle dropped out of their field of view. They also had the chance to shift their location if the view of the obstacle was lost during mid swing. The horizontal distance between their trunk and the obstacle was recorded and this value was later normalized to body height.

The take off distance of a foot scaling an obstacle significantly impacts the clearance height over the obstacle as well as the crossing strategy (Reitdyk & Rhea 2006, Mohagheghi et al. 2004). However, there appears to be a stronger correlation between take off distance and toe clearance for the trail limb than the lead limb. Goggles are known to remove visual information approximately 1 stride before the obstacle (Rhea & Reitdyk 2007); in an attempt to maintain take off distances, 1 meter high position cues were placed on either end of the obstacle to give an AP reference location (Figure 2.4b). One meter high cues were used successfully by Reitdyk & Rhea (2006) to maintain take off distances.

2.5 Data Analysis

2.5.1 Data Processing

All data for both experiments were processed using customized programs within Visual 3D software (C-Motion, Germantown, MD, USA). Kinematic data were first interpolated using a third order spline method with a maximum gap of 12 data points (200 ms) and then subsequently filtered with a zero-lagged second order low-pass Butterworth filter with a 5 Hz cutoff. Residual signals of markers were observed for each rigid body to eliminate sections of trials that produced RMS errors greater than 3 mm. The start and end of each trial was set based on the pelvis location such that the first frame occurred when the pelvis was 1.5 meters before the set global origin. Likewise, the end of each trial was cut off at 3 m beyond the origin (Figure 2.3). These
values were determined in pilot testing so as to optimize sections of data with the lowest IRED residuals.

Events within the gait cycle were used to help extract the dependent variables used for data analysis. The points of heel strike (HS) and toe off (TO) for each trial were determined using a method created by Zeni et al (2008). Briefly, heel and toe marker locations were computed with respect to the pelvis segment in the AP axis. The heel is most anterior to the pelvis at HS, whereas the toe is most posterior to the pelvis at TO. These maximums and minimums were used as HS and TO from heel and toe marker signals respectively. Importantly, this method was designed for level walking and therefore was unable to identify HS and TO as accurately in the obstacle trials. The frame number for HS and TOs were manually adjusted with the aid of the interactive visual model in V3D and the vertical displacement graphs of the heel and toe markers (Figure 2.7). The same individual made all modifications to event timing to minimize the experimenter error.

Lastly, relative joint angles were computed by performing a transformation rotation matrix utilizing the Cardan sequence ZXY (flexion-extension, abduction-adduction, axial rotation). To establish the relative ankle angle, the local coordinate system of the foot was rotated to align with the shank, and likewise, the hip angle was set up such that the thigh coordinate system was rotated to align with the pelvis. A quiet standing trial was collected to create a reference zero for the lower limb angles such that zero degrees equated to the quiet standing position in Visual 3D.
2.5.2 Dependent Variables

1.5.2.1 Experiment I: Level gait

During level gait, five dependent variables were chosen to examine the effects of reduced cutaneous feedback from the dorsal ankle joint. During level walking, a trip is most likely to occur at the time of MTC when the swing foot could make contact with the ground (Berg et al. 1997, Mills & Barrett 2001, Tinetti et al. 1988). Not only is clearance height minimized during MTC but, the horizontal toe velocity is maximized at this same point (Winter 1991). Thus this point during the gait cycle incurs the greatest risk for tripping and due to this rationale, the point of MTC was chosen as a key event of our study on ankle control. In level gait, ankle control at MTC was quantified based on vertical displacement of the toe (MTC), horizontal toe velocity (vMTCx), relative angular positions of the ankle, knee and hip (ankleMTC, kneeMTC, hipMTC) (Figure 2.8). MTC was determined as the local minimum of the toe marker in the vertical axis between TO and HS. The vertical toe displacement was determined by calculating the vertical vector between MTC and the preceding TO. The vMTCx was calculated by taking the first derivative of the horizontal toe coordinate at MTC. Lastly, relative joint angular position, ankleMTC, kneeMTC, and hipMTC at the time of MTC were recorded to evaluate what contribution each joint has to the changes in MTC (i.e. the mechanism behind changes in MTC). Participants initiated each level walking trial with their right foot, enabling collection from three consecutive strides per trial, which were named according to their position relative to the global coordinate systems origin; N+1, N+2, N+3 respectively (Figure 2.3). Test conditions were normalized to the control condition in which no anesthesia was applied and subjects had full vision for each dependent variable and expressed as a percent change.
1.5.2.2 Experiment II: Adaptive gait over an obstacle

During adaptive gait trials (with obstacle), the manner in which the foot crossed the obstacle was of the greatest concern. To accurately characterize this crossing strategy, dependent variables centered on the crossing stride and were characterized as the TO preceding the obstacle until the following TO (Lu et al 2008). To demonstrate the effects of the removal of dorsal cutaneous feedback on the obstacle crossing strategy, variables such as toe clearance (TC), peak elevations (ToePEAK), and time to Peak were calculated for the crossing stride (Figure 2.9). Toe clearance (TC) was defined as the vertical distance between the toe marker and the height of the obstacle when the toe marker crossed the leading edge of the obstacle. ToePEAK was defined as the maximum vertical position of the toe marker in the obstacle crossing step. This would allude to the upward bias of the swing limb over the obstacle. Relative angular positions of the ankle, knee and hip above the obstacle were measured (ankleTC, kneeTC, hipTC) to ascertain whether the changes in TC were due to changes in limb position. McFadyen et al (2007) argued that when stepping over an obstacle without visual information, individuals slow down the swing limb indicating a greater reliance on proprioceptive information for safe obstacle clearance. Therefore, we examined the Time to Peak, which was the time between TO before the obstacle to the Toe peak during obstacle crossing. Lastly, to interpret how the toe was crossing over the obstacle, the horizontal vector between the TC and ToePEAK was measured to indicate the trajectory’s shape (Figure 2.9). A positive toe vector indicated that the toe crossed the obstacle before reaching its maximum elevation, whereas a negative value signified the toe crossing after its maximum vertical displacement. A value of zero exhibits the ToePEAK and TC as the same horizontal position. When ToePEAK occurred before TC, there was an increased risk of foot contact with obstacle since this would indicate that the foot would be on the downward trajectory before
crossing the obstacle. Horizontal take off distances (HDx) were measured as the displacement between the toe marker at TO and the obstacle’s leading edge. This variable was used to compare between the visual conditions to ensure that take off distances were not changing, since HDx could influence clearances and crossing strategies.

2.5.3 Statistical Analysis

Before running parametric tests, data were assessed for normality using a Shapiro-Wilk test and visual inspection to the normal curve. Furthermore, data were tested for homogeneity of variance (HOV) using the Brown & Forsythe’s absolute deviations from group medians. All data were normally distributed (W > 0.90) with the exception of MTC and ankleMTC in the level walking data. These data were log transformed and re-tested verifying that parametric assumptions were no longer being violated (W>0.90, p-value >0.05). Repeated measures ANOVAs were then performed to illustrate the differences in level and adaptive gait experiments separately. A three factor ANOVA (skin x vision x stride) was performed to check whether stride location significantly affected level gait. Analyses revealed no significant main effect or interactions with stride, thus the 3 strides for each trial were averaged. For both experiments, an initial 2x3 way repeated measures ANOVA (skin x site) was executed on perceived sensitivity threshold (PST) scores at each test site to establish the effectiveness of the topical anesthetic in changing sensitivity threshold. For the level gait experiment, a few additional analyses were performed. PST scores were added as a covariate to all ANOVAs to determine whether the degree of anesthetization influenced the changes in gait parameters post analyses. Furthermore, a two-way ANOVA (skin x vision) on the standard deviation of each dependent variable was performed to assess changes in variability across level walking conditions to examine the variance within subjects. In adaptive gait trials, lead and trail limb crossings were evaluated
independently. For each limb, a 2x2 repeated measures ANOVA (skin x vision) investigated the changes in sensory feedback from skin and vision for each of the dependent variables (toe clearance, toe peak, time to peak, take off distance, toe vector, ankleTC, kneeTC, hipTC). Post hoc analyses for both experiments examined pair wise comparisons using a Fisher’s LSD test with a Tukey-Kramer p-value adjustment to correct for multiple ANOVAs. Significance level was determined as $p < 0.05$. All statistical analysis was completed in the SAS program (SAS institute Inc, Cary, NC). Descriptive stats are reported as the means ± SE.

Figure 2.1 Experimental protocol of the trials collected for experiment I (level) and II (adaptive) for each skin block (No anesthetic & anesthetic). The no anesthetic trials always occurred before the anesthetic trials. The pathway (level & adaptive) and vision (full & partial) conditions were block randomized. Within the adaptive gait trials, subjects crossed the obstacle with either right, anesthetized foot as the leading foot or trailing foot.
Figure 2.2 A) The region of anesthesia application (30cm²) and the 3 normalized sites for monofilament testing. Sites 1, 2, 3 were at 10, 50 and 90% from the proximal border. B) Monofilament testing at site 2, displaying buckling of nylon filament perpendicular to the skin surface.

Figure 2.3 Superior view of experimental set up of camera banks, obstacle location as well as the start and end cut offs for each trial. The start of each trial began when the pelvis was 1.5 meters in front of the global origin and the end of each trial was 3 meters after. Three full strides were collected for each trial. Each stride was named based on their location with respect to the origin: the stride to cross the origin and two subsequent strides after were N-X, N+1, N+2 respectively. The red line across the pathway represents the approximate obstacle location for experiment II trials testing adaptive gait. The positive X and Z axes were assigned as the axis of progression and laterally to the right respectively.
Figure 2.4 Marker positions for motion tracking. A) Rigid body set up on Pelvis, Thighs, Shanks and Feet. B) Close up view of Right rigid body and its relative location to the region of anesthesia. C) Digitized anatomical model adopted from Winter (1991).

Figure 2.5 A) Schematic drawing of peripheral vision occluded while wearing the goggles B) Obstacle set up with vertical position cues.
Figure 2.6 Interactive V3D model and toe and heel displacement graphs (y axis) utilized to aid in determining TO and HS using the methods described by Zeni et al (2008).

Figure 2.7 On the left is an interactive V3D model illustrating a left heel strike after crossing over the obstacle. On the right are vertical heel displacements for the left (A) and right (C) heel markers. Graph B and D (left and right respectively) illustrate the relative signal between the pelvis and heel utilized in determining HS using the methods described by Zeni et al (2008). Yellow and red ticks represent left and right HS events respectively. Graph B illustrates the common variance in signal in the crossing stride that was manually adjusted.
Figure 2.8 Schematic of the limb position through the mid swing of level gait and the dependent variables. Toe trajectory is represented by dotted limb and MTC, illustrated here is the local minimum of the vertical toe displacement through swing phase. At the point in the gait cycle, the MTC displacement (1), the relative ankle (2A), knee (2K) and hip (3H) angles and lastly the horizontal toe velocity (3) were extracted.

Figure 2.9 Dependent variables for the Adaptive Gait trials. Numbers indicate dependent variables in the crossing stride for both leading (A) and trailing (B) limb over the obstacle. The red box represents the obstacle; the dotted line shows a sample trajectory of the toe marker. Dependent variables correspond to the following: Toe clearance (1), Toe Peak (2), toe vector (3), Relative ankle (4A), knee (4K) and hip (4H) angular positions while the toe is above the obstacle, take off distance (5) and lastly the time to peak (6) were extracted. Leading limb trajectory (A) is demonstrating a negative toe vector with the peak occurring before the obstacle. Trailing limb toe trajectory (B) is demonstrating a positive toe vector with the peak occurring after the obstacle (greater risk of toe contact with obstacle).
Chapter 3: Experiment I: The Effect of Dorsal Foot Anesthesia on the Control of the Ankle during Gait
(Target Journal: Experimental Brain Research)

3.1 Introduction

Human gait is a highly controlled yet efficient task with an average ground clearance of only 1.5 cm (Winter 1992). Interestingly, changes in ankle angle as little as 2° can result in a ground clearance variability of 0.45 cm, which significantly increases the risk of tripping (Mills & Barrett 2001). Consequently, the control of the ankle joint is rendered critical for successful ground clearance and therefore locomotion.

Several sources of input are known to contribute to passive awareness of the ankle joint. In particular, input from muscle spindles (Gandevia & McCloskey 1976), and joint receptors (Clark et al 1979) are known to influence passive joint position sense. Microneurography studies (Edin 1992; Edin 2002; Aimonetti et al 2007) and passive matching tasks (Edin & Johansson 1995; Simoneau 1997; Lowrey et al 2010; Cordo et al 2012) have led researchers to consider that skin also plays a crucial role in detecting and deciphering movements about joints. To date, the majority of research has examined skin surrounding the finger joints (Edin & Abbs 1991; Collins & Prochazka 1996; Edin & Johansson 1995; Collins et al 2005), the elbow (Collins et al 2005) and knee (Edin 2004), but minimal focus has been on the ankle (Simoneau et al 1997; Lowrey et al 2010). The ankle is of great relevance because of its stated role in postural control during quiet standing (Winter et al 1998) and locomotion (Winter 1992).

Previous literature has emphasized the importance of skin on the plantar surface of the foot for balance equilibrium in quiet stance (Kavounoudias et al 1998; Meyer et al 2004) and for successful locomotion (Duysens et al 1990; Nurse & Nigg 2001; Eils et al 2004). Impeding feedback using cooling evokes increases in body sway (Nurse & Nigg 2001), and decreases in
push-off forces (Eils et al 2004) during locomotion. Additionally, icing results in considerable deficits during gait termination (Perry et al 2001). The role of skin on the lateral border and dorsum of the foot and ankle have also been probed during gait. In particular, locomotor studies have shown how information from this skin is gait phase dependent, and used primarily during swing phase (Duysens et al 1992; Zehr et al 1997). Stimulation of the tibial (plantar skin) and sural nerve (exclusively innervating skin, largely on the lateral border) can alter locomotor patterns during gait (Duysens et al 1990; 1992). Stimulation of superficial peroneal nerve (foot dorsum), in particular, has been associated with ankle joint movements that enhance limb withdrawal and presumably produces improved safety margins during swing (Zehr et al 1997).

While critical information has been generated from this previous work, this experimental nerve stimulation technique cannot isolate the contribution from skin afferents versus spindle afferents using nerve stimulation techniques. Therefore, we cannot be certain that skin as a sensory source is the only modality being manipulated.

Aimonetti et al (2007) used microneurography to reveal that slowly adapting, type II (SA II) afferents on the dorsal and lateral aspects of the ankle had a preferential firing response for plantarflexion. These SA II cutaneous receptors are known to fire in response to movement and changes in position due to their predominant sensitivity to skin stretch (Knibestöl & Valbo 1970; Chambers et al 1972; Edin & Abbs 1991). In support of these findings, Simoneau et al (1997) reported an improvement in movement detection capabilities following taping of the skin on the anterior ankle in a non-weight bearing task; especially in the range of ankle motion analogous to the swing phase of gait. Lowrey et al. (2010) reduced cutaneous feedback on the dorsal region of the ankle with a topical anesthetic and found an increased error in target angle during a passive movement task, primarily into plantarflexion but also into dorsiflexion. With decreased skin
feedback, subjects tended to undershoot the target angle (roughly 1° of dorsiflexion and 2° of plantarflexion). When extrapolated, such deficits of dorsiflexion highlight the potential for an increased risk of foot contact with the ground during locomotion. In summary, there is evidence for the importance of an isolated role of the dorsal ankle skin receptors to ankle control, but such contributions, separate from spindle input, has yet to be determined in a dynamic task such as gait. While phase dependent use of amplified skin input has been demonstrated following electrical stimulation of cutaneous nerves (Zehr et al 1997), tonic removal of skin input via a topical anesthesia would probe the use of natural baseline feedback from the dorsal skin for ankle control. Furthermore, the reduction in sensory feedback from skin is more clinically relevant to aging and pathological populations.

The purpose of this study was to assess the isolated role of dorsal foot skin in ankle control during the dynamic task of locomotion. It was hypothesized that with reduced skin feedback, individuals will employ a more cautious walking strategy demonstrated by, i) increased minimal toe clearances, elicited by flexion at the knee and hip and its dorsiflexion of the ankle, and ii) by decreased toe velocity values.

3.2 Methodology

3.2.1 Subject Characteristics

Experimental protocol conformed to the standards set by the Declaration of Helsinki and had been approved by the University of Guelph Research Ethic’s board. Subjects included five males and seven females (age 21.9±1.97 years; height 173.14 ±11.33 cm; mass 67.41± 13.17 kg) with no history of neuromuscular or musculoskeletal disorders. Individuals provided informed, written consent to participate in the study. The Waterloo Footedness Questionnaire (WFQ) was utilized to determine foot dominance (Elias et al 1997).
3.2.2 Experimental Procedure

Subjects performed 40 block randomized walking trials at a self-selected pace along an 8 meter walkway. All anesthetic trials were performed in the second block (see below). Independent variables included levels of skin (no anesthesia or anesthesia) and visual (full (FV) or partial (PV)) feedback. Four separate experimental conditions included either i) no sensory intervention (control), ii) partial vision (PV), iii) reduced skin feedback (anesthetic), or iv) a combination of partial vision and reduced skin feedback (paired). Participants were instructed to walk towards a target marked on the wall across the room and to initiate each trial with their right foot. Three separate subjects unknowingly received a non-anaesthetic cream as a placebo to control and assess changes unrelated to the removal of skin input and help ensure no confounding psychological aspect was affecting gait strategies. There was still a minimum hour wait time post cream application, and subjects received the same instruction for trials as test subjects.

Experimental set up

Locomotor tasks were recorded using three banks of opto-electric 3D-motion tracking sensors (60 Hz; OPTOTRAK 3020, NDI Inc., Waterloo, ON, Canada). Rigid bodies with three non collinear infrared emitting diodes were securely fastened to the pelvis (ASISs, iliac crests), thighs (greater trochanter, epicondyles), shanks (tibial plateau, malleoli) and feet (5th metatarsal, heel and hallux) bilaterally and anatomically defined using a model adopted by Winter (1998) (Figure 2.4a & c). The rigid bodies were fixed to each segment using double sided skin tape; however the rigid body of the right foot (foot to be anesthetized for reduced skin sensation) was secured with a skin-adhesive (E-Z bond glue, K&R International, CA, USA) to avoid extra proprioceptive cues (Figure 2.4b) as taping of joints has been shown to improve the perception of joint movements (Simoneau et al 1997). Local coordinate systems of each rigid body triad were
transformed to align with the lab global coordinate system. The global coordinate system abided by the International Society of Biomechanics standard of X as the axis of progression, Y as the vertical axis, and Z as the axis projecting laterally to the right.

3.2.3.1 Reducing Cutaneous Input

Cutaneous feedback was reduced through the use of a topical anesthetic cream applied to a shaved, 30cm$^2$ area on the dorsum of the right ankle midway between the malleoli (Figure 2.2a). The topical anesthetic (EMLA® 2.5% lidocaine, 2.5% prilocaine, 2.5 g) was applied evenly over the area and covered with a plastic wrap to maximize absorption. Sensitivity changes of the skin were measured at three test sites within the area (10, 50, 90 % from proximal border; Semmes-Weinstein monofilaments, Stoelting, Co, IL, USA, Figure 2.1b) prior to and following anesthetic application. Perceived sensitivity threshold (PST) was defined as the smallest perceived stimulus at each given test site provided with a verbalized affirmation at least three out of four times (Diamond et al 1989). Note an increase in PST is indicative of decreases in skin sensitivity. Threshold testing occurred one hour after cream application and every 15 minutes subsequently until either our target threshold was achieved or two hours had passed. The target threshold of the topical anesthetic was to evoke a PST similar to the threshold level assigned to identify diabetic neuropathy (PST >10 grams; Holewski 1988).

3.2.3.2 Visual Perturbation

To increase reliance on cutaneous feedback, visual feedback was altered. In a subset of trials, participants wore occlusion goggles that obstructed the lower visual field (level of vision was partial (PV)). This eliminated visual input from the immediate environment and more importantly, information regarding the location of the swing limbs. Before testing began, subjects had the opportunity to walk around the room while wearing the goggles to minimize
learning effects of the change in visual availability. During trials which included the goggles (PV & paired) subjects were instructed to walk towards a target marked on the wall but head and eye movements were not restricted otherwise. Furthermore, each individual’s “obstructed distance” was recorded to obtain magnitude of peripheral vision lost.

3.2.4 Data Analysis

Data were processed in a custom program using Visual 3D (C-Motion, Germantown, MD, USA). Kinematic data were interpolated using a third order spline method (maximum 200 ms gap) and then filtered with a zero-lagged 2\textsuperscript{nd} order low-pass Butterworth filter (5Hz cutoff). The time of each Toe-off (TO) and Heel Strike (HS) were identified and extracted using a method created by Zeni et al. (2008) in order to facilitate isolation of dependent variables (Figure 2.7). Briefly, Zeni and colleagues used the horizontal position of the pelvis marker relative to the heel and toe markers. Since the heel is most anterior to the pelvis at HS and the toe is most posterior at TO, the maximum and minimums of the relative signals designated the gait events respectively. In each trial, data were collected from three consecutive right foot strides. Relative joint angles were computed using a Cardan sequence Z-X-Y by rotating the distal segment of the joint in line with the most proximal segment above the joint and zeroed such that 0 degrees represented a quiet standing position. Movements of the ankle, knee and hip were described as positive if moving into dorsiflexion, knee flexion and hip flexion respectively.

To examine the effects of reduced cutaneous feedback, minimal toe clearance (MTC) became the primary variable of interest as the likelihood of tripping is greatest at minimum toe clearance (Berg et al 1997, Mills & Barrett 2001, Tinetti et al. 1988). Dependent variables included minimal toe clearance (MTC) in the vertical direction as well as the relative positions of the ankle, knee and hip (ankleMTC, kneeMTC, hipMTC respectively), and horizontal toe
velocity (vMTCx) at the instant of minimal toe clearance (Figure 2.7). Relative angular positions of the lower limb would evaluate the mechanism behind the changes in MTC. All dependent variables were normalized and expressed as a percentage of their values determined during the control condition (No Anesthetic, FV).

Finally, to gain insight into the interaction between dorsal skin and vision on swing limb gait kinematics, changes in ankle, knee and hip joint positions for each experimental condition were calculated from control trials. PV changes in angular positions would reveal the role of vision in level walking whereas changes in angular position from anesthetic would delineate the role of skin. Lastly, the changes as result of the paired experimental condition would reveal the integration in the CNS from altered information from these two key sensory systems. We wanted to probe how the CNS potentially integrates this information, so the changes for each joint as a result of PV and anesthetic trials were added together to model a linear relationship, labelled as the “independent sum”. We then compared the integrated sum with the results from the paired experimental condition to determine whether skin and vision combine in a linear fashion to have control the swing limb in gait.

3.2.5 Statistics

The assumptions for parametric testing were verified using a Shapiro-Wilk test for normality and a Brown-Forsythe test for homogeneity of variance. PST changes between skin conditions (no anesthetic and anesthetic) and test site (10, 50, 90% proximal border) were assessed using a 2x3 way ANOVA to test the efficacy of the topical anesthetic in reducing feedback from skin. A three-factor repeated measures ANOVA (skin (2) x vision (2) x stride (3)) was performed to determine if stride to stride differences were present in the data. The analysis revealed that stride location, as an independent variable, showed no significant interaction or
main effects (p=0.52). As a result, data for all three strides were averaged within each trial and a 2 x 2 repeated measures ANOVA (skin (2) x vision (2)) was performed to compare within subject effects. Monofilament PST was included as a covariate in the 2x2 repeated measures ANOVA to assess whether the change in threshold sensitivity influenced to the magnitude of the gait parameter changes. Variability was also assessed using a 2x2 (skin x vision) ANOVA performed on the standard deviation of each dependent variable. Post hoc analyses examined pairwise comparisons using a LSD test with a Tukey-Kramer correction. A one-paired t-test for each of the ankle, knee and hip positions was used to compare the difference of the integrated sum (model) and paired (experimental) joint positions to the predicted value of zero since differences would provide evidence of a non-linear relationship between skin and vision to control the swing limb in gait. Positive changes would represent increases in dorsiflexion and flexion for each of the ankle, knee and hip joints, respectively. Significance level was determined for p < 0.05. All statistical analyses were completed in SAS (SAS institute Inc, Cary, NC). Descriptive statistics are reported as means ± SE unless noted otherwise.

### 3.3 Results

Overall 5 of the 12 subjects reached the target threshold of >10 g consistently for all three sites, while a total of 11 reached significant increases of skin threshold sensitivity for at least one site when compared to pre-cream application thresholds (p>0.05). One subject’s monofilament PST scores reported no change between skin conditions therefore were excluded from the data set and analysis included data from the remaining eleven participants. Topical anesthetic caused significant increased monofilament PST in the ‘Anesthetic trials’ (32.57 g) when compared to threshold in the pre-cream ‘no anesthetic’ trials (1.59 g) averaged across subjects (Figure 3.1). A two-way ANOVA (skin x site) revealed a main effect of skin ($F_{1, 10} = 40.61$, p<0.0001). No main
effect for test site, or significant interactions was found. Interestingly, covariate analyses revealed that individuals who were more influenced by the application of topical anesthetic (i.e. revealed greater decreases in sensitivity thresholds), showed greater changes in all gait parameters examined aside from MTC. Placebo subject’s PST thresholds revealed no effect of anesthetic (skin: $F_{1,10} = 0.14$, $p = 0.87$).

**Gait Parameters**

The effect of reduced skin feedback on the dorsal ankle joint was tested during level walking to determine its importance in ankle control during a functional, active task. The MTC, which is believed to determine the margin of safety through swing, revealed a significant interaction between skin and vision ($F_{1,10} = 6.98$, $p = 0.0247$). Post hoc analysis revealed no significant differences between control (no anesthesia, full vision) and anesthetic with full vision ($p = 0.82$) (Figure 3.2a). However, reduced vision using the goggles resulted in an increase in MTC relative to control (PV: $2.26 \pm 0.073$ cm and control: $1.97 \pm 0.066$ cm; $p = 0.0007$) (Figure 3.2a). Interestingly when both vision and skin input were altered (paired), MTC did not significantly differ from control ($p = 0.54$) but was significantly different than PV alone ($p = 0.0046$).

The horizontal velocity of the toe is greatest at the instant of MTC during the swing phase of gait (Winter 1992). Although, significant changes in MTC were only found with PV, peak velocity ($v_{MTCx}$) showed there was significant interaction between the two sensory systems ($F_{1,10} = 8.46$, $p = 0.016$) controlling toe velocity (Figure 3.2b) and an overall significant decrease with alterations of sensory feedback only from vision ($F_{1,10} = 68.93$, $p < 0.0001$). Toe velocity for control trials was calculated as at $4.39 \pm 0.023$ m/s remaining consistent with the literature (Winter 1992; Patla et al. 1996), and significantly decreased while wearing the goggles (PV;
4.28±0.023 m/s, p<0.0001). The paired condition produced significantly slower velocities compared to control (4.30± 0.019 m/s; p=0. 0004), but was not significantly different from PV trials (p=0.44).

The angular positions of the ankle, knee and hip at the time of MTC were compared across conditions to evaluate the relative contributions of each joint to changes observed in MTC (Figure 3.3). At the ankle joint, a significant increase in dorsiflexion was observed following anesthesia (F₁,₁₀ = 55.12, p<0.0001), and with the removal of vision (PV; F₁,₁₀= 15.97, p=0.003). Compared to control trials where the ankle was slightly plantarflexed at MTC (-2.28±0.23°), ankle dorsiflexion was significantly increased following anesthesia with full vision (anesthesia; -1.34±0.25°; p=0.0018) and with partial vision (paired, -0.86±0.26°; p<0.0001). PV demonstrated no differences from control (p=0.074) but was significantly different from the paired (0.0018). The knee also revealed significant increases in flexion with changes to feedback from skin (F₁,₁₀=75.38 ,p<0.0001). Upon examining post hoc comparisons, a significant increase in knee flexion was also observed following anesthesia (53.7±0.34°) compared to control (52.0 ± 0.28°), ( p=0.0002) but no significant change was observed in knee flexion following the visual intervention (PV; p=0.11).With the paired visual and anesthetic condition, knee flexion was shown to significantly increase to 53.9± 0.27° (p<0.0001). In contrast to the ankle and knee, the hip was unaffected by the change in vision (F₁,₁₀= 1.05, p= 0.33) or skin (F₁,₁₀=0.58, p=0.46). In addition, the degree of hip flexion did not reveal any differences in any pair wise comparisons. Interestingly, there was no significant increase in variability across all dependent variables (p>0.1) and the placebo group gait parameters were unaffected by a change in feedback from skin (p>0.1) yet revealed similar differences as a result of wearing the goggles.
Integrated Sum of Reduced Skin input and Visual Obstruction

Figure 3.4 illustrates the change of angular position from control for the ankle, knee and hip joints at MTC where positive changes reflect increases in ankle dorsiflexion, increases in knee flexion and hip flexion. The independent sum of the PV and anesthetic conditions for the ankle, knee and hip were 1.42°, 2.23°, and 0.34° respectively. Interestingly, the experimental values collected in the paired condition were 1.44°, 2.23° and 0.25° for the ankle, knee and hip respectively. The difference between the integrated sum and paired experimental values were compared to zero using a one-paired t-test and revealed no significant difference for any of the joints (p>0.10).

Table 3.2 Subject Characteristics. WFQ score = Waterloo Footedness Questionnaire. A score of >0 indicates right foot dominance. Obstructed distance expressed as a % of body height indicates the peripheral distance that was obstructed when wearing the goggles.
Figure 3.1 Log PST from monofilaments means and SE (grams) of the three test sites (10, 50, and 90% from the proximal border) on the dorsal foot before EMLA cream application (Pre Anesthetic) and after (Post Anesthetic). Horizontal dotted line represents the target threshold. Raw mean values of each site are above their respective bars. Asterisks (*) denotes statistical significance. Anesthetic significantly increased PST (p<0.0001) over the whole area of interest.

Figure 3.2 The means and standard errors for A) minimal toe clearance (MTC) and B) horizontal velocity of the toe at MTC (vMTCx) for control (no anesthetic, full vision) and each test condition: PV (no anesthetic, partial vision), anesthetic (anesthetic, full vision) and paired (anesthetic, partial vision). No Anesthetic (light gray bars), Anesthetic (dark gray bars). An * denotes significance from control (No Anesthetic FV) † denotes significance between the bars.
Figure 3.3 Means and standard errors for the four conditions; full vision (FV), partial vision (PV; with goggles), No Anesthetic (light gray bars), Anesthetic (dark gray bars). An * denotes significance from control (No Anesthetic FV), and † denotes significance between the indicated bars for the three dependent variables A) Ankle B) Knee and C) Hip at MTC. Position angles indicate ankle dorsiflexion, knee and hip flexion respectively.
3.4 Discussion

Reduction of skin input on the dorsal foot and ankle induced significant changes in joint kinematics during human locomotion. To our knowledge, this study is the first of its kind to confirm that baseline sensory feedback from the skin on the dorsal ankle joint is important for ankle control through the swing phase of gait. Furthermore, it was shown that a reduction in cutaneous sensory information over the ankle joint can also generate significant changes at the knee. We were also able to demonstrate interactions between skin and visual inputs for the swing limb during unobstructed level gait; visual ex proprioception appears to have a less dominant role in controlling the joint positions through swing phase of gait. The functional relevance of these changes and the influence of cutaneous feedback during the swing phase of gait are discussed below.

Figure 3.4 The change from control condition of the ankle, knee and hip joint position for each test condition; partial vision, anesthetic, or paired (partial vision and anesthetic). The independent sum represents the mathematical sum of the partial vision and anesthetic experimental test condition changes for each joint. Positive angles indicate ankle dorsiflexion, knee flexion and hip flexion. Asterisks (*) denote significant difference from control. A one-paired t-test used to compare the difference for the ankle, knee and hip changes from control between paired and independent sum revealed no statistical differences between the two groups (p>0.1).
Afferent input from cutaneous receptors of dorsal foot can modulate gait

The minimal height at which the foot clears the ground through swing imposes the greatest risk of foot contact with the ground or an obstacle (Mills & Barrett 2001). Controlling this height is vital for evading trips and falls and relies heavily on proprioceptive feedback. It was hypothesized that reduced cutaneous input on the ankle would decrease proprioceptive information about foot position, resulting in increased minimal toe clearances (MTC) as a means of increasing safety margins. Our results, however, showed no changes to MTC suggesting that individuals were able to preserve the vertical displacement of their foot through the swing phase of gait following a reduction in skin input. Although this is did not follow our projected hypotheses, this result was in accordance with unchanged toe clearances reported for elderly populations (Winter 1990; Mills et al 2008) and patients with diabetic neuropathy (Dingwell et al 1999) when compared to healthy controls. Marked deficits in afferent feedback in conjunction with preserved clearance heights highlight the adaptability of locomotor patterns to prioritize conservations of the end point control of the toe. Nonetheless, each respective study found pronounced increases in MTC variability within these sub-populations (Mills et al 2008; Dingwell et al 1999) suggesting a lack of control of limbs which may increase the risk of encountering trips and falls. Conversely, in the current study of young healthy individuals a decreased cutaneous sensory input from the dorsal ankle did not produce any changes to variability (p>0.05). We propose some possible explanations for these differences. Firstly, outliers for each dependent variable beyond ± 2 standard deviations from the mean were removed from the data to satisfy the assumptions for parametric statistics, but a second and more functional explanation is that the intervention of anesthetic cream application effectively reduced only one modality of proprioception in young healthy adults. In the elderly and those with
diabetic neuropathy, the loss of somatosensory feedback will extend to skin on both the plantar (Well et al 2003; Perry 2006) and dorsal (Yip et al 2013) surface of the foot as well as muscle spindle sensitivity as a result of age related muscle change and peripheral sensory loss (Swash & Fox 1972; Burke et al 1996; Madhaven & Sheilds 2005). This widespread reduction in sensory information experienced by geriatric and clinical populations may predispose them to increases in MTC variability during gait when compared to a young healthy population with temporary and partial sensory loss.

Despite the unchanged MTC following anesthesia, reduced cutaneous input in young adults did modify angular positions at the time of MTC for all three of the joints examined (knee>ankle>hip). Significant increases in dorsiflexion (0.9°) and knee flexion (1.6°) but interestingly, no significant changes at the hip were observed at MTC in trials with reduced cutaneous feedback around the ankle joint compared to control (Figure 3.3). Although these changes appear to be small, sensitivity analysis of angular changes of these joints during gait have revealed that isolated the changes as small as 1.4° at knee and 2.0° and at the ankle can generate a clearance differences of up to 0.5 cm (Winter 1992). Recall that average minimal toe clearances are only 1 cm thereby making the observed changes in this study potentially detrimental to making contact with the ground, especially since changes were observed with both the knee and ankle.

The increase in ankle dorsiflexion emphasizes the attempt to increase safety margins but also potentially amplifies feedback from the other inputs providing proprioceptive information about the ankle. Dorsiflexion of the ankle at MTC would increase safety margins and reflects a more conservative gait strategy similar to modifications observed previously with altered cutaneous feedback across different foot regions (Eils et al 2004). Cooling of the foot sole
results in reduced plantarflexion and dorsiflexion at push-off and heel strike respectively and characterizes the use of cautious gait (Eils et al 2004).

Secondly, by increasing ankle dorsiflexion, individuals may be using other sources of proprioceptive feedback at the ankle by engaging antagonistic muscle spindles to a larger extent. Roll & Vedel (1982) reported greater activation of muscle spindles during active muscle lengthening at the ankle likely as a result of increased spindle activity through stretch. Dorsiflexion would also increase the degree of skin stretch on the posterior ankle likely targeting activations of SA II afferents which have demonstrated preferential firing following movements producing skin stretch (Edin & Abbs 1991; Aimonetti et al 2007). Furthermore, this amplified input from skin has been exploited by taping the ankle to improve joint movement detections (Simoneau 1997). While either explanation is plausible, it is likely that the increased dorsiflexion is as a result of an integration of the two strategies; an increased input from alternate sensory sources enhance joint position sense along with increased ground clearance, together provide assurance for sufficient ground clearances.

The increase in knee flexion following anesthesia (Figure 3.3b) may be an additional strategy to prioritize safety when the joint position sense at the ankle is compromised. Increased knee flexion was also observed following stimulation of the superficial peroneal nerve to further elevate the swing limb (Zehr et al 1997). Changes to the swing limb’s knee angle are the most sensitive to provoke augmented clearances (Winter 1992), so it seems logical to use a knee strategy when increased safety margins are in demand. In fact, when the foot crosses over an obstacle of varying heights, Patla and colleagues (1996) reported the knee as the primary joint to increase flexion when compared to level walking.
Although loss of dorsal skin information appears to play a critical role in the swing phase by increasing ankle dorsiflexion and knee flexion, these mechanisms were unable to explain the unchanged MTC. Observation of the joint angles (Figure 3.4) indicates that skin located on the ankle can produce coordinated changes to sequential joints but perhaps the MTC was in part maintained through adaptations beyond the sagittal plane of the three joints observed since locomotor strategies often aim to minimize energy expenditure in level walking (Chou et al 1995). Further examination of the frontal plane of movement as well as the stance limb joint positions are required to increase our understanding of how this region of skin is affecting the toe trajectory in swing. For example, knee extension of the stance limb or pelvic roll in swing would both act to increase mean toe clearances (Winter 1992). Furthermore, decreasing vertical impulse forces in the stance limb would increase the vertical position of the whole body COM would also serve as another alternative (Patla & Prentice 1991).

These modifications to the limb position during swing phase were accompanied by the reduction of the horizontal toe velocity, which subsequently provided more time to fine tune peripheral changes of the foot through swing (Figure 3.2b). Decreased horizontal toe velocity has been reported in other studies involving elderly and clinical populations (Winter 1990; Raspovic 2013) as well as in studies that implement ankle muscle vibrations during gait (Verschueren et al 2002a). By decreasing the velocity of the forward progression of the swing limb, individuals increase the amount of time available to adjust to the altered sensory feedback and generate the necessary modifications to gait. Collectively, a decrease in toe velocity in conjunction with the observed limb angle changes, demonstrate the importance of cutaneous feedback for the control of the swing limb in level gait; the presence of available input from muscle spindles, remaining skin and online visual cues do not compensate for the lack of effective cutaneous feedback on the
dorsum of the ankle. This finding suggests a trade-off between safety and efficiency (i.e. no change in MTC), perhaps in attempt to minimize mechanical energy expenditure and maintain locomotor trajectory.

*Removal of exproprioceptive input of swing limb causes a more cautious walking strategy*

The sudden change in visual input (i.e. the loss of exproprioception when wearing the goggles) caused individuals to increase their minimal toe clearance through swing. Only one other study has examined the use of visual peripheral cues during level over ground walking and reported no changes to MTC with lower visual field occlusion in a healthy population (Graci et al 2009). In that study, participants only experienced peripheral loss in one eye and complete occlusion in the other. This unilateral difference of visual information could also potentially explain the variations in their results from the bilateral reduction in lower visual field cues in this study. Several other studies have used bilateral lower occlusion goggles in a more challenging obstacle crossing step and found increases in toe clearances over the obstacle as a strategy to increase safety margins (Reitdyk & Rhea 2006).

While changes in visual input resulted in significant increases in toe clearance, subjects exhibited no significant joint angle changes for the ankle, knee or hip but did produce slight increases in the flexion of the ankle and knee joints (Figure 3.3 & 3.4). This indicates that individuals are perhaps relying on a combination of increased flexion of lower limb joints to attain increased safety margins through swing. That is not to say that alternative strategies are not also being employed to influence limb elevation (frontal plane) but from our investigation, no significant changes in the sagittal plane were observed. Furthermore, without visual input, there was a significant decrease in horizontal toe velocity suggesting a more cautious strategy as a result of increased acuity for lower limb kinesthesia (Patla et al 1996; Reitdyk & Rhea 2006).
Overall, the change in visual input appears to cause strategies independent to those observed following anesthesia but nonetheless, employ similar underlying mechanisms i.e. conservative control of gait, in the absence of reliable sensory feedback.

*Paired reduction in dorsal skin input and exproprioception*

The visual perturbation was incorporated into the study to emphasize the effects of skin feedback since previous work, probing the use of the somatosensory and vestibular systems; observed greater effects when input from vision was eliminated (Bent 2004; Bove et al 2009; Gomez 2009). It was hypothesized that any locomotor changes observed following either sensory perturbation would be exacerbated when paired together. Contrary to the initial hypothesis, no differences in minimal toe clearance were found between the paired sensory perturbation condition and control (Figure 3.2a). It is possible that when feedback from skin and vision are both compromised, individuals adjust typical online locomotor control and increase reliance on descending input from the CNS for feed forward control, or alternatively, use proprioceptive feedback from other modalities such as muscle spindles. On the other hand it is possible that individuals adapted or exhibited learning effects following a change in visual input over consecutive steps and trials as due to the anesthesia effect, the PV condition was always tested before the paired condition. Graci and coworkers (2009) examined the change of MTC over repetitions with lower visual field occlusion, but found no effects. Nonetheless, this repetition effect was only examined over six trials so perhaps familiarization of altered visual feedback had yet to occur. Additionally, altering visual feedback using prism goggles has reportedly resulted in a complete adaptation of gait parameters after 10 trials such that initial changes were abolished and returned to baseline (Alexander et al 2011). In our study, a minimum of 10 trials were collected for PV walking and subjects wore goggles to and from the
start position on the 8 meter walkway. Since paired trials always occurred following PV, adaptation of the visual perturbation could account for the differences observed for paired MTC. In an attempt to minimize learning effects, subjects were given the opportunity for a few practice trials before collection began but it is possible this practice may have been insufficient.

The angular joint position changes observed at MTC were similar in the paired condition to that following anesthesia alone (Figure 3.3 & 3.4). Subjects significantly increased the magnitude of ankle dorsiflexion (1.3°), and knee flexion (1.8°) in the paired condition, to parallel the kinematic changes in ankle dorsiflexion (0.9), and knee flexion (1.6) respectively following anesthesia. This gave rise to the idea that when both systems are perturbed, the control strategy employed relies on skin feedback for joint coordination through swing phase more so than vision. The literature has frequently made arguments that vision is the dominant sensory source to control locomotion (Patla 1998; Marigold 2008) and our study is the first of its kind to challenge that the somatosensory system, and specifically skin feedback as also plays an important role to control locomotor synergies as the availability of online visual cues.

The changes observed following a visual perturbation, while small, were shown to be additive to the skin response. In fact, the difference between the integrated sum of change (PV + anesthetic) versus the experimental values (paired condition) were not different from zero indicating they are in fact the same. This would suggest a linear integration in the sagittal plane between skin and vision to coordinate the lower limb during human level walking. At the present time, the relative contribution between each modality remains unknown. Since no significant changes were observed following the visual perturbation for each of the joints but significant changes were observed following anesthesia, could suggest that the involvement of skin surpasses the role of vision to control joint positions in swing phase of level gait.
Feedback from Cutaneous Mechanoreceptors can create joint position changes of Entire Limb

The role of input from muscle spindles, frequently highlighted as the primary source of proprioception, has been probed using vibration during gait however has resulted in evoking changes in only the joint being vibrated (Verschueren et al 2002a). Verschueren et al (2002a) found that vibration of tibialis anterior muscle during gait generated kinematic changes at the ankle, but did not affect angular positions at the knee or hip. From our work, we have shown that reducing skin on the ankle can modify gait kinematics not only at the joint of the overlaying skin (ankle) but can also create changes at a more proximal joint (knee), suggesting that cutaneous feedback may influence intersegmental coordination during level walking. These findings corroborate with the locomotor reflex work from Zehr et al (1997) and Duysens et al (1990;1992), which demonstrated that stimulation of cutaneous nerve terminals can modify locomotion patterns of the entire limb and create functionally relevant changes to joint kinematics. Despite the high fidelity of muscle spindles for joint position sense, input from skin may be more important to integrate proprioception from the whole limb and generate pragmatic sequential joint position coordination for motor tasks.

The benefits and pitfalls of topical anesthesia to probe skin contribution in movement control

When removing skin feedback with a topical anesthetic, we can be more confident over previously used methods (e.g electrical stimulation, cooling) that we are isolating sensory input from the skin alone (Zehr et al 1997). Stimulation of a nerve i) lacks the ability to differentiate afferent excitation from specific receptor types ii) is difficult to isolate without disturbing surrounding and underlying structures and iii) only considers the role of abrupt, increased feedback. Alternatively, cooling of the skin using ice permits greater assurance that cutaneous
receptor activity is targeted but its effects are short-lived and unique to receptor type (Lowrey et al 2013). Since topical anesthetic cannot penetrate past the dermal layer of skin, we can be confident that we are exclusively affecting cutaneous mechanoreceptors. Moreover, the stability and longevity of its effects make using a topical anesthetic more practical when testing over multiple trials. Lastly and most importantly, by reducing skin input we are considering the use of natural baseline information from skin. Testing this way also more naturally mimics circumstances in elderly and patients with neuropathies. Unfortunately, a major pitfall with anesthesia is the dosage and surface area allowance and secondly, the time-consuming process required for the anesthetic to take full effect (1-2 hours).

In light of the observed modifications to locomotor patterns, the area of skin anesthetized was only 30 cm² in size (limited based on dosage of cream), but this gives an even greater consideration to the importance of cutaneous input, given the availability of remaining cutaneous input. Previous work in our lab demonstrated this area to be of sufficient size to generate impedance to ankle joint perception (Lowrey et al 2010), regardless of the fact that there was remaining skin on the posterior ankle and that muscle spindles were left intact. We have now extended this substantial involvement of cutaneous feedback in ankle control to a locomotor task; one that incorporates sensory input from all systems as well as descending control from the CNS.

Conclusions

We have demonstrated that following a reduction in cutaneous feedback from the dorsum of the ankle joint, significant changes to locomotor patterns are observed in level walking. Anesthesia of the foot dorsum skin influenced changes in joint position at the ankle, knee and hip through swing phase such that minimal toe clearances were preserved. When paired with the loss
of online visual cues from goggles, similar results were generated. In contrast, the isolated loss of online vision did not significantly alter any one joint position but did tend towards increasing flexion to conceivably result in the observed amplified toe clearances. For each test condition there were also marked decreases in velocity ultimately demonstrating characteristics of a more conservative gait with unreliable peripheral feedback. The influential role of skin has been previously shown in passive tasks but this work has now established a role for foot dorsum skin in active locomotor control. In addition, by combining aberrant feedback from skin and vision, this work has provided evidence that the involvement of skin may rival that of vision for controlling the swing limb in gait. Future work would benefit from the investigation of skin’s influence in a more challenging but functionally relevant task such as obstacle avoidance.
Chapter 4: What is the role skin on the dorsal ankle joint during Adaptive Gait for Lead and Trail Limb over an Obstacle?
(Target Journal: Experimental Brain Research)

4.1 Introduction

Joint position sense at the ankle joint is of great importance given the high degree of ankle control required to manage toe end point trajectory in order to safety ambulate through our environment (Winter 1992; Moosebhoy & Bard 2006). While spindle information is known to contribute to joint position sense (Roll & Vedel 1982), cutaneous mechanoreceptors have more recently been highlighted as an essential modality in proprioception. This has been demonstrated by their high fidelity to decipher magnitudes and directions of joint movements about the fingers (Edin & Abbs 1991; Collins & Prochazka 1996), elbow (Cordo et al 1994), knee (Edin 2001) and ankle (Lowrey et al 2010) during passive tasks. While all four types of cutaneous receptors likely contribute to ankle control, it is proposed that large proprioceptive contributions come from the slowly adapting, type II (SA II) receptor populations, which are exquisitely sensitive to skin stretch overlaying joints (Chambers et al 1972, Edin & Johansson 1995)–over the dorsum of the foot, in the case of the ankle joint. Ground clearances are minimal through swing (Winter 1992) so dorsal skin may be paramount for fine control of the ankle during gait transitions.

Work by Zehr and colleagues (1997) examined the effects of superficial peroneal nerve stimulation (recruits primarily cutaneous afferents from dorsal skin) through phases of the gait cycle. These researchers found that this cutaneous input modified muscle activation and joint kinematics during swing phase. Specifically, the early swing phase demonstrated strong suppression of Tibialis anterior activity and concomitant facilitation of the biceps femoris to passively plantarflex and actively flex the knee to minimize impact force and help clear an impending obstacle. While cutaneous stimulation can be informative to elicit corrective
stumbling responses, it is important to establish the ability of skin to provide ‘online’ feedback for proprioceptive ankle control.

Encountering an obstacle in the path of progression requires that the swing limb be precisely controlled to ensure sufficient clearances. It is largely unknown how the CNS uses sensory input from independent sources such as skin to modulate locomotor synergies to successfully navigate obstacles. Furthermore, when stepping over an obstacle, each limb that crosses requires two completely different strategies depending on whether the foot crosses first (leading limb) or second (trailing limb). Not only does each limb require different mechanical joint movements, but available visual input while crossing also varies for each foot. The leading limb can be seen in the periphery while crossing but the trailing limb is always out of view and could therefore potentially impose a greater reliance on kinesthetic input (Patla et al 1996).

To date, much of the human adaptive gait (obstacle avoidance) literature has focused on sensory contributions from vision. It is generally accepted that the visual system is used for the planning of locomotor strategies and scanning the environment for potential hazards (Hollands & Marple-Horvat 1996; Patla & Vickers 2003; Drew et al 2008). Recent work within our group investigated the role of the foot dorsum skin in human locomotion across a level surface. We found significant changes in joint angles and foot trajectory outcomes following a reduction in skin information (Experiment 1). It remains to be established whether foot dorsal skin information is utilized during adaptive gait, a condition which may be more relevant to our continuously changing environment than level walking. In the current study we will examine the effect of reduced cutaneous input to assess whether the loss of skin information would alter kinematics of the ankle during a complex motor task. Previous work in this area revealed that a tonic reduction in skin input on the foot dorsum from anesthesia or cooling decreased joint
position sense for a passive stationary ankle task (Lowrey et al. 2010). It was hypothesized that for the leading limb, anesthesia of the dorsal ankle would generate an increase in toe clearance and peak toe elevations on the obstacle crossing stride, and these increases would be generated by increases in ankle dorsiflexion as well as hip flexion. Furthermore, when the trailing limb was anesthetized, there would be an increase in toe clearance and peak projections of the trail toe due to increases in knee flexion and ankle plantarflexion.

4.2 Methodology

4.2.1 Subject characteristics

Twelve healthy young adults (age 21.6±2.06 years; height 172.17±11.21 cm; lower leg length 44.25±2.96 cm) were recruited for the study. Subjects had no history of any self-reported neuromuscular or musculoskeletal disorders, or any lower limb injuries within the last 6 months. Waterloo Footedness Questionnaire (WFQ) was utilized to determine foot dominance; a resulting score of > 0 indicated right foot dominance (see Appendix). Prior to testing, subjects provided informed, written consent; the protocols was approved by the University of Guelph Research Ethics Board and complied with the Declaration of Helsinki.

4.2.2 Experimental Procedure

To evaluate the role of cutaneous receptors on the dorsal foot during adaptive gait, subjects performed 40 randomized walking trials down an 8 meter walkway that included an obstacle in the path. Subjects were instructed to walk towards a target on the wall at a comfortable pace and cross the obstacle in a way that felt natural. Prior to data collection, a starting position was determined such that individuals inadvertently crossed over the obstacle with the same foot that initiated the trial; subjects started with either foot based on a pre-set randomized order (starting location was adjusted accordingly). Independent variables included
skin (No anesthetic, Anesthetic), vision (Full vision (FV), Partial vision (PV)), and foot (Lead, Trail; which was always set as the right limb) yielding a total of 8 conditions (skin (2) x vision (2) x foot (2)). A minimum of five trials per condition were collected. Intact skin sensation trials (No Anesthetic) were collected first, followed by test trials with reduced cutaneous feedback (Anesthetic). Additionally, trials were presented in blocks of visual feedback (FV or PV) but the crossing limb within each block was randomized. The anesthetized right foot either crossed the obstacle first (Lead) or second (Trail) to determine the role that this skin region played for these particular phases of obstacle crossing.

4.2.3 Experimental set up

Kinematic data were collected at 60Hz using an opto-electric 3D motion capture system (OPTOTRAK 3020, Northern Digital Inc., Waterloo, ON, Canada). The cameras recorded locomotion from rigid body platforms of infra-red emitting diodes securely fastened to the pelvis, thighs, shanks and feet bilaterally via double sided skin tape; however the rigid platform of the right foot (foot to be anesthetized for reduced skin sensation) was secured with a skin-adhesive (E-Z bond glue, K&R International, CA, USA) to avoid extra proprioceptive cues (Figure 2.4b) as taping of joints has been shown to improve the perception of joint movements (Simoneau et al 1997). Anatomical landmarks were referenced to each rigid body using a digitizing probe to create a modified biomechanical model as follows: the Pelvis (Anterior superior iliac spines, Iliac crests), thighs (Greater Trochanter, medial and lateral epicondyles), shanks (Tibial plateau, medial and lateral malleoli), and feet (5th metatarsal, Hallux, heel) (Winter 1998). The global coordinate system was digitized to align with the International Society of Biomechanics standard –X as the axis of progression, -Y as vertical and -Z was arranged, laterally to the right with a calibrated camera RMS error of <0.40mm.
4.2.3.1 Skin

Topical anesthetic cream was used to reduce cutaneous input and was applied to a shaved, 30 cm$^2$ area on the dorsum of the right foot midway between the malleoli (Figure 2.4a). EMLA® cream (2.5% lidocaine, 2.5% prilocaine) was applied in a thick layer over the area and sealed with a plastic wrap dressing to maximize absorption. The cream remained on the skin between one to two hours. Semmes-Weinstein monofilaments (Stoelting, Co, IL, USA) were used to measure the sensitivity changes before and after the application of the anesthetic. Perceived sensitivity threshold (PST), defined as the smallest stimulus force indicated by the subject, was measured at three sites within the area (10, 50 and 90% from the proximal border of the EMLA® application area). Changes in sensitivity were measured one hour post application and in 15 minute intervals subsequently, until the target threshold was attained or a maximum of two hours had passed. The target threshold of the topical anesthetic was to evoke a PST similar to the threshold level assigned to identify diabetic neuropathy (PST >10 grams; Holewski 1988).

4.2.3.2 Vision

Subjects either stepped over the obstacle with complete vision (FV) or wore goggles that obstructed the lower half of the visual field (PV) (Figure 2.5a). Each individual’s ‘obstructed distance’ was measured to establish the extent of peripheral vision ‘loss’ via the basketball goggles. To measure the obstructed distance, subjects walked towards a marked target (X) across the room while the obstacle was in position and were asked to stop as soon as the obstacle was no longer in their field of view. They also had the opportunity to adjust their position if the view of the obstacle was lost during mid swing. The horizontal distance between their trunk and the obstacle was recorded and this value was later normalized to body height. The goggles prevented visual input of the swing limbs (exproprioception) as well as visual information about
the environment ahead (1.8 meters or approximately 3 steps). Subjects had the opportunity to walk around the lab while wearing the goggles prior to data collection in order to become familiar with the change in visual information and to minimize learning effects.

4.3.2.3 **Obstacle set up**

To induce adaptive gait strategies, an obstacle was placed in the path of progression. The obstacle consisted of a wooden dowel suspended by two metal brackets. It was set to 45% of each subject’s lower leg length in height (20.3 cm obstacle height on average) and was approximately 96 cm in width (approximately the width of a doorway) (Figure 2.4b). The obstacle height was chosen to mimic the height of an object that individuals would still cross over rather than circumvent in a natural environment (Patla et al 1997) but also large enough to generate biomechanical changes different to level walking (Patla et al 1991). Previous researchers demonstrated that removal of visual information in the approach phase (two strides before obstacle) over an obstacle influences take off distances (Patla et al 1991; Rhea & Reitdyk 2007). Moreover, these take off distances are strongly correlated to the clearance height above the obstacle (Rhea & Reitdyk 2006; Mohagheghi et al 2004). Therefore, two 1-meter tall wooden dowels stood vertically on either obstacle end to give an anterior-posterior reference location. Similar position cues were successfully used by Rhea & Reitdyk (2006) to maintain take off distances.

4.2.4 **Data Analysis**

A custom program using Visual 3D (C-motion, Germantown, MD, USA) was created to process the data. Signals from each rigid body were interpolated with a third order spline method and filtered with a zero-lagged 2nd order low-pass Butterworth filter with a 5 Hz cut-off. Events within the gait cycle were located and extracted using a method established by Zeni et al. (2008).
In brief, heel and toe marker locations were computed with respect to the pelvis segment in the AP axis. The heel is most anterior to the pelvis at heel strike (HS), whereas the toe is most posterior to the pelvis at toe off (TO). These maximums and minimums were used as HS and TO from heel and toe marker signals respectively. This technique was originally designed to ascertain TO and HS during level ground walking, therefore some HS post obstacle data were slightly variable. As a result, events were manually inspected and frame number of event was shifted if necessary with the aid of the interactive visual model in V3D and the vertical displacement graphs of the heel and toe markers (Figure 2.5). These gait events were used to isolate crossing stride data and calculate some of the dependent variables (described below).

Relative joint angles (ankle, knee, and hip) were computed by aligning the local coordinate systems (LCS) of the distal joint segment with LCS of the proximal segment using a Cardan sequence, Z-X-Y (flexion-extension, abduction-adduction, axial rotation) (Cole et al. 1993).

Dependent variables were focused around the obstacle crossing stride. Crossing stride was defined as the TO before the obstacle to the following TO (Lu et al. 2008). To investigate the effects of reduced dorsal cutaneous feedback on the obstacle crossing strategy, several kinematic variables were calculated from the right limb trajectory during the crossing stride (Figure 2.6). At the obstacles leading edge, the following measures were taken: toe clearance (TC) above the obstacle, and the relative hip, knee and ankle angles (HipTC, Knee TC, and AnkleTC). ToePEAK was the maximum elevation of the toe in the crossing stride. Together, TC and Toe PEAK give an indication of the margin of safety and the upward bias of the swing limb over the obstacle; in addition, joint angles establish how joint kinematics contribute to changes in TC. McFadyen and colleagues (2007) argued that when stepping over an obstacle without visual input, individuals slow the movement of the swing limb indicating a greater reliance on
propriocceptive information for safe obstacle clearance. Therefore, we examined time to peak (TimePEAK) to establish how the cutaneous feedback affected the crossing velocity of the foot. This was measured as the time between TO (before the obstacle) to its maximum elevation in the crossing stride. Horizontal take off distance (HDx) was determined as the horizontal displacement between TO and the obstacles leading edge and was used to assess whether clearances were simply due to differences in HDx (resulting in different trajectories over the obstacle). Finally, the horizontal toe vector was the horizontal displacement between TC and Toe peak and was examined to obtain a sense for crossing strategy and trajectory control (Berard & Vallis 2006). Increases in the horizontal toe vector would be indicative of a greater tendency to reach maximum elevation after clearing the obstacle and potentially a greater risk for foot contact while clearing the obstacle. All dependent variables were normalized to control trials (which served as a baseline of intact sensory feedback) and expressed as a percent of control (No Anesthetic, Full Vision).

As stated previously, to control the lead and trail limbs, strategies used by the CNS over an obstacle in the travel path are quite different (Patla et al 1996; McFadyen et al 2007). For this reason, we elected to conduct the statistical analyses on dependent variables separately for the lead and trail limbs.

4.2.5 Statistical Analysis

Parametric test assumptions were verified using a Shapiro-Wilk test for normality and Brown-Forsythe homogeneity of variance test. A 2 x 3 repeated measures ANOVA (skin x site) identified the changes in PST between the intact and anesthetized skin at each test site. Two-way repeated measures ANOVA (skin (2) x vision (2)) were performed on the lead and trail limb trials independently for each of the dependent variables. Post hoc analyses were run to determine
significance of the pair wise comparisons using a LSD test with a Tukey-Kramer adjustment to correct for multiple ANOVAs. Significance was determined as p<0.05. A custom SAS program (SAS Institute Inc, Cary, NC) was used to perform all statistical analyses. Descriptive stats are reported as the means ± SE.

4.3 Results

WFQ revealed one minor left foot dominant (score = -1) and eleven right foot dominant individuals. As a result, the left foot dominant participant’s data were excluded and analyses were performed on the data from the remaining eleven individuals. Semmes-Weinstein monofilaments were used to quantify cutaneous feedback prior to and post topical anesthetic application. After a maximum of two hours of anesthetic application, while most subjects saw an increase in threshold, only 5 subjects of the 12 achieved the target threshold of greater than 10 grams of force consistently for all 3 sites but every subject’s PST increased significantly between skin conditions. The 2-way ANOVA (skin (2) x site (3)) revealed a main effect of skin (F₁,₅₅ = 40.61, p<0.0001) for PST scores. Baseline PST prior to EMLA® cream application was 1.59 g and increased to 32.57 g following anesthesia (collapsed across sites). Increases in perceived thresholds are indicative of decreases in sensitivity.

4.3.3 Obstructed distance and Crossing Errors

The goggles were found to obstruct between 77% and 133% of the visual path relative to each individual’s body height (1.8m of environment ahead). Seven of the eleven subjects made contact with the obstacle during testing but never more than once, equating to less than 1.4% of all trials. All but one foot contact was made while wearing the obstruction goggles and the
majority of contacts were made with the trail limb. In addition, about half of the contacts were made in trials with the anesthetized limb. These trials were removed from further analyses.

4.3.4 Lead Limb

When anesthetic was applied to the lead limb, toe clearance was significantly affected by both skin ($F_{1,10} = 17.53, p = 0.0019$) and vision ($F_{1,10} = 94.67, p < 0.0001$) but no overall interaction effect ($p=0.12$) was found. In control trials (No Anesthetic, FV) participants reached a toe clearance (TC) of 15.0 cm above the obstacle, similar to values reported in the literature (Lu et al. 2008). Post hoc comparisons revealed significant increases of TC to 21.0 cm while wearing the goggles (No Anesthetic PV, $p < 0.0001$) and 16.75 cm with reduced cutaneous input alone (Anesthetic, $p = 0.0098$). When both sensory systems were impaired (paired), the increasing effect was greatest, resulting in clearances of 21.5 cm ($p < 0.0001$) (Figure 4.1). Peak toe projections also significantly increased following reductions in cutaneous ($F_{1,10} = 13.89, p = 0.0039$) and visual ($F_{1,10} = 147.3, p < 0.0001$) feedback. Similar to TC, ToePEAK significantly increased from 34.4 cm (control) to 39.4 cm with PV ($p < 0.0001$) and 36.5 cm with anesthetic ($p = 0.0472$). When reduced skin and visual were paired, input had the greatest increase in Toe Peak, reaching a height of 42.2 cm ($p < 0.0001$) (Figure 4.1). Interestingly, the horizontal toe vector revealed a greater tendency for the toe peak to occur after the obstacle following reduction of skin input ($F_{1,10} = 1747, p = 0.0019$) whereas in control and PV (No Anesthetic), the toe peak occurred before the toe crossed the obstacle.

Relative ankle angular position at the time of TC demonstrated a main effect of skin ($F_{1,10} = 5.06, p = 0.046$) but post hoc comparisons between control and each test condition revealed no significant effects (anesthetic ($p = 0.88$), PV ($p = 0.52$) or paired ($p = 0.95$)). Post hoc tests also revealed that hip position at TC was significantly more flexed in both PV ($88.1^\circ, p = 0.0088$) and
paired (90.1°, p=0.0002) trials when compared to control trials (83.7°). However, the knee did not reveal any changes between skin (p=0.08) or vision (p=0.07) conditions. Relative joint position changes for the ankle knee and hip are illustrated in Figure 4.5. HDx was unchanged from the reduction of skin input (p=0.76) or from wearing the goggles (PV, p=0.18), but was larger with the paired intervention (p=0.03). Time to Peak increased consequently from reductions in skin (F$_{1,10}$=36.32, p=0.0001) and vision (F$_{1,10}$=56.88, p<0.0001). These changes were significant for all pair wise comparisons.

On the whole, the loss of effective skin input on the lead limb resulted in increased TC, toe peak, and horizontal clearance vector, as well as a longer time to cross over the obstacle. Interestingly, these modifications of the toe trajectory in the crossing stride were not due to a change in ankle position hip position, or take off distance.

4.3.4 Trail Limb

The trailing toe clearance was unaffected by reduced skin input (F$_{1,9}$=0.52, p=0.49) but was significantly increased while wearing the obstructive goggles (F$_{1,9}$=12.03, p=0.007). TC significantly increased from 17.9 cm in control to 19.7 cm and 20.7 cm in PV (p=0.015) and paired (p=0.032) respectively (Figure 4.3). Equally, ToePEAK showed no change following anesthetic (F$_{1,9}$ = 0.03, p=0.88) but significantly increased from the loss of vision (F$_{1,9}$=23.34, p=0.0009). The trend was continued with angular positions of the ankle (F$_{1,10}$= 17.61, p=0.0018), knee (F$_{1,10}$=32.93, p=0.0002) and hip (F$_{1,10}$=17.43, p=0.0019) (Figure 4.6), where the angular position at TC was affected by a change in visual input (main effect), but no modifications as a result of skin (p=0.32). Post hoc comparisons revealed an increase in degree of dorsiflexion with the goggles (PV; 4.33°, p=0.021) when compared to the plantarflexion ankle in control trials (-1.41°) (Table 2). The knee increased magnitude of flexion over the obstacle for both PV (5.78°;
p=0.0046), and paired (5.82°; p=0.0047) conditions, however the only change in hip angle at TC was with the pairing of anesthetic and goggles, creating a 6.51° increase in flexion (p=0.0059). The horizontal toe vector was unaffected by the change in skin (p=0.42) or vision (p=0.071). Skin had no impact on HDx ($F_{1,10}=0.02; p=0.88$) although the loss of vision in the approach phase significantly increased HDx in both PV (p=0.0021) and paired (p=0.0027) trials. Finally, in following with all of the other variables of the trailing limb, time to peak was unaffected by reductions in skin input via anesthetic ($F_{1,10}=0.73; p=0.42$) but was shown to increase following a reduction in vision ($F_{1,10}=42.02; p<0.0001$) as seen in Figure 4.3.

Collectively our results show that the trail limb was unaffected by the loss of cutaneous input on the dorsal surface of the foot while crossing the obstacle; confirmed unanimously by all dependent variables. On the contrary, it appears that the reduction in visual input of the approach phase is capable of dramatically modifying the toe trajectory and lower limb movement over an obstacle. Raw values for all dependent variables can be found in Tables 1 and 2.
Table 4.1 Raw Means ± SD and of Toe Clearance (TC), toe peak, Horizontal toe vector, Time to Peak and Horizontal distance (HDx) for both Lead and Trail limb for each test condition, as well as significant interactions between conditions.

<table>
<thead>
<tr>
<th></th>
<th>TC (cm)</th>
<th>Toe PEAK (cm)</th>
<th>Horizontal Toe Vector (cm)</th>
<th>Time to Peak (sec)</th>
<th>HDx (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEAD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>15.0± 6.45</td>
<td>34.4± 6.4</td>
<td>-3.80± 0.11</td>
<td>0.30± 0.04</td>
<td>0.90± 0.12</td>
</tr>
<tr>
<td>PV</td>
<td>21.0± 6.3a</td>
<td>39.4± 7.8a</td>
<td>-2.52± 0.13</td>
<td>0.32± 0.04a</td>
<td>0.93± 0.15a</td>
</tr>
<tr>
<td>Anesthetic</td>
<td>16.8± 5.3a</td>
<td>36.5± 6.1a</td>
<td>0.41± 0.10a</td>
<td>0.32± 0.03a</td>
<td>0.91± 0.11</td>
</tr>
<tr>
<td>Paired</td>
<td>21.5± 6.0abc</td>
<td>41.5± 5.2abc</td>
<td>0.38± 0.11abc</td>
<td>0.35± 0.04abc,abc</td>
<td>0.95± 0.13abc,abc</td>
</tr>
<tr>
<td><strong>TRAIL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>17.9± 9.3</td>
<td>36.3± 8.6</td>
<td>0.28± 0.07</td>
<td>0.22± 0.03</td>
<td>0.24± 0.08</td>
</tr>
<tr>
<td>PV</td>
<td>19.7± 7.4a</td>
<td>38.4± 6.4a</td>
<td>-2.95± 0.10a</td>
<td>0.24± 0.04a</td>
<td>0.30± 0.07a</td>
</tr>
<tr>
<td>Anesthetic</td>
<td>18.8± 6.6</td>
<td>36.8± 7.2</td>
<td>1.32± 0.08</td>
<td>0.22± 0.03</td>
<td>0.25± 0.07</td>
</tr>
<tr>
<td>Paired</td>
<td>20.7± 7.3a</td>
<td>40.1± 5.4a</td>
<td>0.42± 0.08</td>
<td>0.24± 0.03a</td>
<td>0.30± 0.08a,b</td>
</tr>
</tbody>
</table>

“a” denotes significance from control, “b” from anesthetic, “c” from PV
Significance is p < 0.05

Table 4.2 Raw Means SE of relative Ankle, Knee and Hip Position at the time of Toe Clearance. These values are reported for both the lead and trail limb for each condition. Significant interactions are denoted in superscripts. Ankle dorsiflexion, Knee flexion and hip flexion are represented by positive angular positions.

<table>
<thead>
<tr>
<th></th>
<th>AnkleTC (°)</th>
<th>KneeTC (°)</th>
<th>HipTC (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEAD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>7.1± 0.8</td>
<td>111.7±1.5</td>
<td>83.7±1.3</td>
</tr>
<tr>
<td>PV</td>
<td>6.8± 0.8</td>
<td>112.1± 1.4</td>
<td>88.1±1.2a</td>
</tr>
<tr>
<td>Anesthetic</td>
<td>7.7± 1.0</td>
<td>117.9±1.6</td>
<td>84.8±1.1</td>
</tr>
<tr>
<td>Paired</td>
<td>7.8± 1.0</td>
<td>112.0± 1.8</td>
<td>90.1±1.1ab</td>
</tr>
<tr>
<td><strong>TRAIL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>-1.4± 1.4</td>
<td>121.4±1.8</td>
<td>36.7±1.2</td>
</tr>
<tr>
<td>PV</td>
<td>4.3± 1.4a</td>
<td>127.2±1.7a</td>
<td>39.9±1.4</td>
</tr>
<tr>
<td>Anesthetic</td>
<td>-2.6± 1.5</td>
<td>122.1±1.5</td>
<td>37.4±0.8</td>
</tr>
<tr>
<td>Paired</td>
<td>1.82± 1.3</td>
<td>127.2±1.4b</td>
<td>43.2±1.3ab</td>
</tr>
</tbody>
</table>

“a” denotes significance from control, “b” from anesthetic, “c” from PV
Significance is p < 0.05
Figure 4.1 Average and standard error for the horizontal take-off distance (HDx), toe clearance (TC), toe Peak and time to Peak in the for the leading limb. White bars represent No Anesthetic and Dark bars represent Anesthetic trials. * signifies significance from Control (No Anesthetic, FV). Lines over the bars indicate significance between conditions.

Figure 4.2 Representative data of the sagittal plane (x, y) toe trajectory of the leading toe over the obstacle for control (solid black), PV, (solid gray), Anesthetic (dotted gray) and Paired (dotted black) trails. Crossing stride shown for toe-off before the obstacle until the subsequent toe-off.
Figure 4.3 Average and standard error for the horizontal take off distance (HDx), toe clearance (TC), toe Peak and time to Peak in the for the leading limb. White bars represent No Anesthetic and Dark bars represent Anesthetic trials. * signifies significance from Control (No Anesthetic, FV). Lines over the bars indicate significance between conditions.

Figure 4.4 Representative data of the sagittal plane (x, y) toe trajectory of the trailing toe over the obstacle for control (solid black), PV, (solid gray), Anesthetic (dotted gray) and Paired (dotted black) trails. Crossing stride shown for toe-off before the obstacle until the subsequent toe-off.
Figure 4.5 Mean (SE) for the Ankle (top), knee (middle), and hip (bottom) positions at the time of toe clearance for both the Leading limb. * denotes significance from control trials (No Anesthetic, Full vision). Lines denote significance between conditions. Significance is $p<0.05$. 
Figure 4.6 Mean (SE) for the Ankle (top), knee (middle), and hip (bottom) positions at the time of toe clearance for both the trailing limb. * denotes significance from control trials (No Anesthetic, Full vision). Lines denote significance between conditions. Significance is p<0.05.
4.4 Discussion

Skin on the dorsal surface of the foot and ankle is important for controlling the leading limb over an obstacle but does not influence the trailing limb. Each limb that crosses over an obstacle is known to have different mechanical and stability demands as well as different reliance on visual cues (Patla et al 1996; 1998; Mohagheghi et al 2004). The results from this study supplement previous literature on the phase dependent use of visual input and provide additional evidence that somatosensory input from skin surrounding the ankle joint is also phase dependent for the control of the limb over an obstacle.

Obstacle Take off distance, position cues and visual perturbation

Adaptive gait is a more complex task than level walking as it requires feed forward and online visual cues to plan successive steps and make appropriate limb adjustments to avoid stability threats. Vision is used to plan foot placements approximately two steps ahead (Patla &Vickers 2003); we purposefully compromised visual input at this key point in the gait cycle via goggles which obstructed the visual surround approximately three steps (1.8m) anterior to the subject. Foot placement before an obstacle is critical as it can directly influence toe trajectory characteristics. In the current study, we minimized changes to the horizontal foot placement that may be prevalent in the visual obstruction trials, by using vertical poles that provided cues as to obstacle location. This enabled assessment of foot placement changes due to anesthesia and not foot trajectory, per se. These vertical position cues clearly assisted with the preservation of take off distances (HDx) of the leading limb in the PV condition; similar findings were reported by Reitdyk & Rhea (2006), whose take off distances returned to their full vision condition with the supplementation of position cues. However, in the current study, when vision loss was paired with anesthesia, we observed increases in HDx. These increases may have resulted from reduced
integration of kinesthetic and visual cues to facilitate foot placement. Recently, work with cats walking on a treadmill probed the coupling between visual input for locomotor planning and proprioceptive feedback and found when treadmill speed (which provided proprioceptive feedback) and obstacle approaching speed (which provided visual feedback) were incongruent, there were marked decrements in step planning and changes in swing trajectories (Drew et al 2008). Insufficient locomotor planning resulted in subjects reverting to a safer obstacle crossing approach whereby they initiated the crossing stride farther away from the obstacle (Drew et al 2008; Rhea & Reitdyk 2007; Patla 1998). Interestingly this is a similar strategy commonly adopted in elderly subjects for obstacle crossing paradigms (Chen et al 1991).

Our subjects did not benefit from position cues for appropriate trailing foot placements before the obstacle. This finding disagrees with those from Reitdyk & Rhea (2006) whose trail HDx were the same regardless of visual availability with position cues in place. The differences in our findings could be due to the larger obstructed visual distance (1.8 m) compared to the peripheral obstruction in the latter study (1.2 m) It is also possible that these differences may have resulted from our vertical position cues, which were only 1 meter in height versus the 2 meter cues utilized from Reitdyk & Rhea (2006). In agreement with our data, Graci (2010) also used position cues but did not observe restorations of take off distances in the trailing limb. They found with lower peripheral occlusion, subjects started trailing limb crossing stride further away than with full vision. Trailing foot placement in the current work was much closer to the obstacle (~0.3 m) compared to leading foot placement (~0.9 m) and at this distance, the position cues were perhaps no longer in view, especially for taller subjects. As a result of the influence of take off distance, the following discussions take into account and evaluate dependent variables with consideration of the changes in take off distance.
**Leading Limb relies on both dorsal foot cutaneous receptors and visual online cues**

Significant changes in the leading limb toe trajectory were observed for all test conditions (anesthetic, PV, paired). When visual cues were removed, or subjects had reduced proprioceptive feedback from skin on the ankle, or both, increases in the leading limb’s margin of safety (increased toe clearance) and an upward bias of the swing limb (increased toe peak) was observed. These results suggest that with unreliable sensory feedback, a conservative strategy is employed to prevent foot contact with the obstacle. This corroborates findings from similar studies that have systematically altered visual information (Patla 1998; Mohagheghi et al 2004; McFadyen et al 2007). Although no study to date has directly investigated the role of skin feedback during obstacle avoidance and adaptive gait strategies, there is a wealth of literature that supports the importance of cutaneous sensory feedback for joint position sense and movement detection for similar adaptive tasks (Edin & Abbs 1991; Collins et al 2005; Lowrey et al 2010). In addition, skin feedback evokes locomotor reflexes in both cats (Forssberg 1975; 1979) and humans (Duysens et la 1992; Zehr et al 1997), which are believed to serve as protective mechanisms when executing obstacle avoidance strategies. In previous research, perturbation of the skin in the swing phase via mechanical or electrical stimulation elicits withdrawal responses and amplified toe trajectories, in support of a cautious adaptive strategy. An additional cautious strategy is to increase the time to traverse the obstacle. In the current study, the concomitant increase in time taken to cross the obstacle (time to peak) has a twofold purpose i) in case of contact with the obstacle, slower velocities minimize detrimental effects from the limb’s momentum ii) slower velocity equals greater time to use additional proprioceptive feedback to fine-tune limb trajectory; especially when denied online visual input. Interestingly, there was an additive affect with paired reductions to skin feedback and visual...
input for the time to peak. This reinforces our interpretation that subjects use extra precaution and take more time to fine tune their toe trajectory over the obstacle. This also demonstrates an advanced degradation of locomotor control when there are more erratic changes in sensory feedback. Due to the fact that position cues were successful in preserving take off distance for the lead limb in single sensory perturbations, we can be confident that increases in TC, toe peak, and time were due to changes in inherent crossing strategy and not because of changes in foot placement before the obstacle. However, when reductions from skin and vision were paired, take off distances were significantly increased, indicating that when drawing conclusions regarding the changes observed in other variables, take off distance must be considered.

Following anesthesia, there were no significant interactions between test conditions and the control condition but there was a main effect of skin trending towards dorsiflexion. It is possible that, given the height of the obstacle (~20.6 cm), the ankle is already dorsiflexed so much that it is approaching the boundaries of its range of motion and is therefore mechanically constrained. Winter (1987) reported subjects have a 9.6° maximum degree of dorsiflexion in level gait, and while the lead toe was over the obstacle it was dorsiflexed roughly 7°. However, more likely explanation for the limited ankle dorsiflexion is that while sufficient ankle proprioceptive feedback may be obtained from stretching of both the skin on the posterior ankle and spindles within ankle plantar flexor muscles, additional proprioceptive sources arise at the knee and hip joints. During normal locomotion, the swing phase is predominantly a passive event as it requires minimal muscle activity. Conversely, through swing phase over an obstacle, there is much larger active participation from most of the lower limb muscles, leading to dramatically different toe trajectories (Patla et al 1996). As a result, dorsal skin may perhaps not be as important for ankle control while crossing over an obstacle since muscle spindle activity is
higher. Hulliger (1993) reported vast increases in gamma motor drive and thus, spindle sensitivity, when cats were exposed to a foreign motor task compared to straight level walking.

Although main effects of skin were seen for each of the ankle, knee and hip, post hoc comparisons of the changes produced by anesthetic (independent of vision) compared to control did not reach significance (Figure 4.5) even though the toe clearance was significantly higher. This would suggest that perhaps some combination of minor flexion from all three joints could be accredited to the increasing toe clearances as well as strategies beyond the depth of the sagittal plane following anesthetization of the skin on the ankle joint. Conversely, the joint strategy to increase TC over the obstacle appears to be clearer while wearing the goggles (PV & paired). To elevate the lead swing limb, subjects utilized a hip strategy, which is commonly exhibited for lead limb obstacle crossing with increasing obstacle heights (Patla & Prentice 1995). Patla & Reitdyk (1993) reported that increased hip flexion as a function of obstacle height would be essential for subsequent foot landing.

*Trailing Limb does not depend on cutaneous feedback from the dorsal ankle joint*

Similar to the leading limb, PV and paired conditions generated increased TC, toe peak, and time to peak in the trailing limb but in opposition with our hypotheses, there was no effect from anesthesia for any of the parameters investigated. These similar conservative strategies have been previously reported with declines in the visual availability (Patla 1998; Mohagheghi et al 2004). In our work, along with increased TC, toe peak and time to peak, the trailing limb also exhibited significant increases in take off distance with visual impairment. As discussed earlier, the take off distance has a direct influence on other crossing stride parameters i.e. toe clearance and notably, these correlations are even stronger for the trailing limb than the leading limb (Mohagheghi et al 2004). That is not to say that there are not other factors that are influencing
crossing stride characteristics when online visual information is unavailable. We simply suggest that the take off distances can clearly influence the alterations observed in toe trajectory. Further investigation using regulated take off distances would be required to isolate the effects of the cutaneous and visual perturbations.

When wearing the goggles (PV & paired), individuals increased the magnitude of knee flexion while the trailing limb was over the obstacle, similar to knee flexions observed from increasing obstacle heights (Patla et al 1996). Increasing flexion about the knee seems logical as it is the primary joint in the trailing limb that can generate high clearances with greatest efficiency (Patla et al 1996). Surprisingly, with occlusion of the lower visual field (PV), there were significant increases in the degree of ankle dorsiflexion while the trailing limb was over the obstacle in paired trials, and the hip was found to be in a more flexed position. These findings are unusual and difficult to interpret since both would increase the likelihood of contacting the obstacle and are characteristic joint movements as the limb descends towards the ground in preparation for heel contact. However, upon examining the joint angle profiles over the entire crossing stride, it would appear that the behaviour of both the hip and ankle are a result of temporal differences from increased take off distances while wearing the goggles (PV & paired). These joint positions are characteristic of limb positioning distinguished in the downward trajectory in preparation of foot landing (Patla & Reitdyk 1993). Interestingly, these changes in take off distance do indicate that there is an effect on crossing strategy when the goggles are present, and vision is removed. Conversely, anesthesia did not cause any significant changes to sagittal joint position changes of the ankle, knee or hip however when anesthetic trials (anesthetic & paired) are compared to no anesthetic trials (control & PV), trends could be observed where there was a degree of increasing plantarflexion (Figure 4.2a); this would make
sense from a mechanical perspective to avoid toe contact with the obstacle. Recall that following anesthesia, the leading limb employed the strategy of dorsiflexing the ankle so as to facilitate successful clearance over the obstacle. Taken together, these alternate strategies suggests the possibility of a phase dependent use of skin at the ankle parallel to the cutaneous reverse reflex responses demonstrated by Duysens, Zehr et al (1992; 1997).

It is interesting that no changes were observed in any of our variables in the trail limb following anesthesia; many researchers claim a reliance on proprioceptive cues for the trail limb because of the inability to use visual input to guide the limb (Patla 1998; Mohagheghi et al 2004; Reitdyk & Rhea 2006). Our results suggest that skin on the dorsal surface of the foot is not involved in the control of the trailing limb. If there is an increased reliance on kinesthetic cues during visual obstruction, input must be being obtained from other proprioceptive sources on the posterior ankle or from the underlying muscle spindles. It should be noted that more than half of our subjects (7/12) made contact with the obstacle at least once, and the majority of foot contacts were made with the trailing limb while wearing the goggles. Previous research has found that toe trajectories are exaggerated following contact with the trailing limb up to 8 trials after the trip. Therefore increases in clearances and peaks could have been influenced by an over-compensation following obstacle contact. These findings have also been extended to afferent feedback and reflex pathways for corrective stumbling responses, seen in cats (Forssberg 1975) and humans (Zehr et al 1997).

It appears that vision during the approach phase is imperative for the trailing limb crossing stride but also corroborates the idea that instead of the sight of the limb itself, it is the foot placement before the obstacle that is essential for the trailing limb control (Reitdyk & Rhea
2006). When approach phase vision was unavailable, individuals increase trail take off distances in an additional attempt to avoid the obstacle.

**Limitations**

There are a few limitations that must be considered when interpreting the changes in peripheral feedback from skin on the ankle during adaptive gait control of the swing limb. Firstly, joint position change while the toe was over the obstacle was examined in the sagittal plane alone, which limited our understanding of how toe elevations and toe clearances were altered. This does not consider joint position changes that occur within the frontal plane such as ankle inversion/eversion, adduction/abduction of the hip or pelvic roll, all of which could have effects on the toe trajectory of the leading limb. Secondly, this study did not examine the inter-limb coordination between the affected (anesthetized) and unaffected limb. Although not supported with current literature, it is possible that in anesthetized trials, the trailing limb was conditioned by afferent information from intact lead. Lajoie et al (2012) investigated the effects of proprioceptive feedback and efferent copy of lead limb input to affect trail limb mechanics and reported no significant alterations in trail limb trajectory as a result of lead limb sensory manipulations (adding mass to the limb). These authors suggested that information about obstacle crossing gained through visual input is sufficient to develop a neural representation of the obstacle allowing for successful crossing by the trailing limb. In addition data from Lajoie and colleagues (2012) provide evidence to refute the possibility that the leading limb influenced the trailing limb via efferent copy. Furthermore, Lajoie and colleagues (2012) only looked at stepping over an obstacle from standing which does not consider steady state gait or the impact of dynamic optic flow versus static visual input (Patla 1998). Furthermore, these authors only studied effects from altered proprioceptive input from Golgi tendon organs or muscle spindles.
but failed to consider the input of skin. Future investigations may be required to assess the use of skin for inter-limb coordination.

Summary & Conclusions

This study is the first of its kind to investigate the role of proprioceptive input from cutaneous receptors during adaptive gait. Mohagheghi et al (2004) declared that control of the lead limb depends more on on-line visual information whereas the trail limb is more reliant on feed forward visual and online kinesthetic cues. By removing online visual input, our results indicate that online visual input is important for lead limb control. More importantly, however, we provided evidence that the lead limb uses skin on the ankle to control the swing limb trajectory over an obstacle despite online visual availability. In essence, the use of online visual cues cannot compensate for deficits in proprioceptive feedback from skin. In addition, with concomitant removal of skin and vision, the effects were amplified, indicating that the integration of input from visual and somatosensory sources aid to control toe trajectory path and that each sensory modality alone is not capable of correcting and preserving locomotor strategies.

In contrast to the work by Mohagheghi and coworkers (2004), based on our work it would appear that online visual cues (removed by goggles) also influence trail limb kinematics. This was demonstrated by the increased margin of safety and upward bias of the swing limb while crossing the obstacle. Even with vertical position cues trailing limb trajectories were different from control values. The results from this study have provided convincing evidence that online kinesthetic importance is unlikely obtained from the skin on the dorsal surface of the ankle for the trail limb during adaptive gait. Further investigation is required to substantiate the claim of a greater reliance of online kinesthetic cues.
Chapter 5: General Discussion

The aim of this research was to gain an understanding of whether cutaneous receptors on the dorsal surface of the ankle joint play a role in limb control during an active locomotor task. By examining the contribution of skin on the dorsal foot during gait we hoped to further advance our understanding of how the ankle joint is controlled during this highly conserved motor task. To this end, we first investigated how altered skin feedback affected level gait (Experiment I) and subsequently observed how, or if, this role was altered when subjects were required to adapt their ongoing gait patterns to accommodate environmental restrictions (Experiment II). Previous work has reported differences between level and obstructed walking (Patla et al 1996, Patla & Reitdyk 1993, McFadyen et al. 2001). Each task exhibits significantly different ground reaction force impulses, mechanical joint powers and electromyography profiles (McFadyen et al 2001). There are also striking increases in muscle spindle sensitivity from level walking to the novel task of stepping over an obstacle in the cat (Hulliger 1993). Therefore, by including the obstacle task we did not seek to determine the direct differences between level and obstructed gait, but to introduce a challenging and more complex task to investigate task dependent roles of dorsal ankle skin. An additional, but not primary, objective of this thesis was to also observe the interaction between the role of skin and lower visual field cues on motor pattern behaviours.

Afferent feedback from skin on the ankle is utilized to control locomotor patterns in walking

Responses to reduced cutaneous information on the dorsum of the foot through the swing phase of gait resulted in clear changes to locomotor strategy; velocity of the toe was reduced, joint positions of the ankle and knee acted to facilitate ground clearance (increased flexion), but it remains unknown what served to maintain minimal toe clearance (MTC) and thus locomotor efficiency following anesthesia. With the reduced visual input, there was a response to optimize
movements to ensure successful clearance over the ground however there were minimal changes to the sagittal joint positions. To achieve higher MTC with PV, individuals are perhaps changing the stance limb position, or generating a movement in the frontal plane instead (Winter 1992). Interestingly, when both skin and vision became unreliable, velocity was significantly reduced and the joint positions of the ankle and knee joints at MTC were significantly altered and coordinated such that MTC was unchanged. Similarly to the locomotor behaviour in the anesthetic trials; the ankle was more dorsiflexed, the knee was more flexed and the hip was more extended to parallel effort towards maintaining efficiency. To compensate for the loss of skin, individuals may be tuning into proprioceptive sources such as muscle spindles and remaining skin on the limb since dorsiflexion would increase the stretch (and therefore activity) of both sensory sources on the posterior leg (Roll & Vedel 1982; Aimonetti et al 2007). Taken together, our findings for level walking suggest a previously downplayed input of skin to control the swing limb during level gait may rival that of vision; however further investigation must be made to substantiate the relative importance of skin to all forms of visual input.

*Skin on the dorsal surface of the ankle joint influences the leading limb but not the trail*

Foot dorsum skin appears to be used phase dependently; when the anesthetized foot crossed the obstacle as the leading limb, it responded differently than when it was the trailing limb. Reduced skin input triggered a conservative strategy through increased toe clearances, toe peaks and time to peak but only trends towards increasing flexions of the ankle, knee and hip. The trailing limb position and toe trajectory, however, were unaffected from reduced cutaneous input. When only visual cues were removed (PV), the lead and trail limb had similar responses such that each limb increased every crossing dimension to avoid the obstacle except for lead
limb take-off distance. An interesting finding of our work is the idea that vision is important for the trail limb control; this is quite different from what has been previously reported. Past work has suggested that kinesthesia is the primary sensory source for trail limb crossing. Specifically, Mohagheghi and coworkers (2004) reported increased clearances in both limbs when vision was occluded in the approach phase, but *only the leading limb* was affected by removal of vision in the obstacle crossing phase. These authors claimed that other sensory sources were being used to influence the trajectory of the trail limb. The paired reductions of skin and vision in our work further increased toe clearance, toe peak and time to peak for both the lead and trail limb however, the joint positions to create the increased TC were different between limbs. Observed increases in toe clearance were driven by hip flexion for the lead limb and knee flexion for the trail limb. These findings suggest that altered visual and skin afferent feedback triggered a response to exercise caution and increase crossing parameters for both limbs, but the strategy to accomplish each limb elevation was different. It should be noted that the trailing limb was only affected by changes in vision, and as a result, changes in the trailing limb during the paired perturbation are likely driven by the visual restriction more so than the change in afferent feedback from skin.

*Implications of skin loss on the ankle joint*

From the two experiments for this thesis we provided insight into the role of the skin on the dorsum of the ankle; it contributes to the control of the ankle joint and swing limb during level walking and obstacle avoidance. Taken together, the findings from both studies illustrate the potential task (level & adaptive) and phase (lead & trail) dependent uses of skin atop the ankle and foot and can add to the work regarding cutaneous reflexes and phase reversal uses of skin during human locomotion (Duysens et al 1992; Zehr et al 1997). While wearing the goggles,
there was a uniform response regardless of task or phase during locomotion to prioritize safety via increased toe clearance and toe peak. These changes in toe trajectory support current literature, which highlight the use of online and feed forward visual information to guide locomotion (Mohagheghi et al 2004). Without visual assurance, individuals revert to safer alternatives no matter the context. Lastly, there appears to be task dependent contributions from skin following anesthesia when paired with visual obstruction from the goggles; pairing responses behave more like anesthetic responses in level walking but more like visual responses in adaptive locomotion. The functional application of losing skin information on the ankle is described below.

Through swing phase, the responses to reduced skin input highlight the goal of efficiency during level walking yet features safety when crossing an obstacle; however the stability threat for each scenario should be considered. With level walking, there is no apparent stability threat in sight within the immediate environment whereas with an obstacle, individuals must exercise vigilance to avoid obstacle contact. When there is no impending stability threat (level ground), toe clearances must be maintained to conserve energy, but with the inherent risk of tripping, toe clearance is magnified to guarantee avoidance of the obstacle. This provides explanation for changes to leading limb control following anesthesia but fails to interpret the trailing limb’s response. As the leading limb is crossing over the obstacle, it propels the center of mass forward and away from the base of support (trailing stance limb) but as the trailing limb crosses, the COM is brought towards the leading stance limb making the latter act inherently more stable than the former (Patla et al 1996), emphasizing the necessity for control of the lead limb. As such, the trail limb does not require the same level of feed forward control despite the impending stability threat. This finding provides evidence that unreliable sensory feedback from skin above
the trailing ankle joint may not immediately impose a threat to postural stability resulting in little need to change toe trajectory.

Aside from a stability perspective (e.g. impeding threat of tripping), there is also the potential for sensory re-weighting to occur. Our findings suggest that additional proprioceptive or visual inputs can perhaps compensate for the loss of cutaneous feedback in the swing limb during level walking to preserve clearances. It would also appear that alternate sensory inputs cannot compensate for the loss of skin at the ankle while crossing over the obstacle with the leading limb, individuals then revert to a safer alternative by increasing crossing stride dimensions. Lastly, the lack of changes in the trail limb demonstrates that proprioceptive input from the skin about the ankle is not essential for controlling the trail limb over an obstacle. Adequate trail limb elevation is primarily driven by knee flexion (Patla et al 1996); therefore, perhaps knee afferent information is more pertinent in trail limb control, not to mention that ankle muscle spindles are left intact using topical anesthetic as an intervention.

It is intriguing that the small area of anesthesia (30 cm$^2$) applied to the ankle joint could create such widespread changes in level gait. Muscle spindles provide rich joint position information (Roll & Vedel 1982; Roll et al 1989; Cordo et al 1995) and have been probed during locomotion through vibration, but researchers found that muscle vibration has isolated effects to only the joint being perturbed (Ivanenko et al 2000; Verschueren et al 2002). Interestingly, in our work not only did the small area of anesthetic affect the joint position at the ankle, but it also promoted changes at the knee and hip to suggest that perhaps during a sequenced motor pattern such as walking, skin afferent feedback potentially plays a role in intra-limb coordination. In contrast, the changes in joint position that were observed to increase toe trajectory were isolated to one joint in either the lead or trail limb over an obstacle following a sensory perturbation.
Muscle activity is dramatically higher in the swing limb over an obstacle, than over the ground (Patla et al. 1991) and parallels with increased spindle fusimotor drive (Vallbo et al. 1971). Work on decerebrate cats has shown cutaneous stimulation can inhibit fusimotor drive (i.e., muscle spindle sensitivity) during locomotion (Murphy et al. 1999) and a similar inhibition has been demonstrated in standing humans (Aniss et al. 1990). Interestingly, recent work from our lab has shown a potential reversal of the inhibitory gamma drive following the reduction of skin input such that spindle sensitivity was increased (unpublished data). Therefore, by reducing skin input on the dorsum of the ankle, it is possible that individuals capitalize on the increased spindle sensitivity to determine the joint position of their ankle.

5.4 Implication of Findings and Future Directions

Age-related degradation of sensory systems parallel the increasing risk of trips and falls in the elderly (Kovas 2005, Winter 1990). Studying neurological contributions to gait and obstacle avoidance are imperative to the advancement of rehabilitation protocols and implementation of risk preventative measures. The extensive changes to limb position through the swing phase during level gait provides evidence that young, healthy individuals are capable of coordinating changes in the lower limb to preserve clearance values and likely capitalize on the input from skin input and online visual cues. However, in an individual with a peripheral neuropathy or even during healthy aging, the decline in afferent feedback in the lower limb would be more widespread, encompassing decreased acuity in somatosensory feedback from skin and spindles (Holewski et al. 1988; Lord et al. 1996; Kararizou et al. 2005). Furthermore, geriatric populations could also be confronted with the additional deterioration in visual and vestibular function (Glasser & Campbel 1998; Johnson et al. 2007). The widespread deficits in these populations also progress over a lifetime (Perry 2006) whereas our sensory intervention
substantially suppressed cutaneous information atop of the foot and ankle in an acute time frame of only two hours. Perhaps young healthy adults are able to quickly adapt to the altered sensory input and employ appropriate alternate strategies as a result of the access to redundant sensory input whereas the same affluence is not necessarily available in geriatric or pathological populations. It is unknown how these populations would react if exposed to the same abrupt change in sensory input, however it can be projected that they would have an increased likelihood of trips and falls

Locomotion is a fundamental human motor task that is critical for our activities of daily lives. The findings from this current thesis work have shown that skin on the dorsum of the foot is utilized for the control of the lower limb through the swing phase of gait as well as during obstacle crossing with the leading limb. The trailing limb was unaffected by the loss of feedback from this region of skin suggesting that proprioceptive control of the trailing limb occurs via other modalities of afferent feedback. Further investigation into which sensory source is imperative for trailing limb control is still required.
Waterloo Footedness Questionnaire – Revised

Instructions: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle RA or LA (for right always or left always). If you *usually* use one foot circle Ru or Lu, appropriate. If you use both feet equally often, circle Eq.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

<table>
<thead>
<tr>
<th>Question</th>
<th>LA</th>
<th>Lu</th>
<th>Eq</th>
<th>Ru</th>
<th>Ra</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Which foot would you use to kick a stationary ball at a target straight in front of you?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. If you had to stand on one foot, which foot would it be?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Which foot would you use to smooth sand at the beach?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. If you had to step up onto a chair, which foot would you place on the chair first?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Which foot would you stomp on a fast moving bug?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. If you were to balance on one foot on a railway track, which foot would you use?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. If you wanted to pick up a marble with your toes, which foot would you use?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. If you had to hop on one foot, which foot would you use?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Which foot would you use to help push a shovel into the ground?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. During relaxed standing, people initially put most of their weight on one foot first Leaving the other leg slightly bent. Which foot do you put most of your weight on?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Is there any reason (ie injury) why you have changed your foot preference for any of the above activities?</td>
<td>YES</td>
<td>NO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Have you ever been given special training or encouragement to use a particular foot for certain activities?</td>
<td>YES</td>
<td>NO</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Waterloo footedness questionnaire was used to determine each individual’s foot dominance. The questionnaire consisted of a series of 10 questions that required participants to record which foot they would preferably use in a series of activities (see appendix). These activities included actions that required a preferred stance foot for balance, or a preferred motioned foot. Participants could either answer always, usually or equally for either foot. A score between -2 (Left always) and +2 (Right always) was assigned to each answer and then summed. A positive outcome on the test meant the subject was right foot dominant, whereas a negative result indicated a left foot dominant subject. For the purpose of this study, only right foot dominant individuals were chosen (Taken from Elias et al 1997)
Subject Screening Questionnaire

Subject Code:
Age:
Sex:
Height:
Weight:
Leg Length:

Please complete the following questionnaire to enable the researchers to determine your suitability for inclusion in the following study:

The Effect of Dorsal Foot Anesthesia on Gait Control

- Are you pregnant, trying to become pregnant or breastfeeding? Yes No
- Are you epileptic? Yes No
- Do you have high blood pressure? Yes No
- Do you have glucose-6-phosphate dehydrogenase deficiency? Yes No
- Have you ever had an allergic reaction to lidocaine or prilocaine? Yes No
- Do you have severe kidney or liver disease? Yes No
- Do you easily become dizzy? Yes No
- Do you have any musculoskeletal disorders or diabetic neuropathy? Yes No

- From your previous experience, what is your sensitivity level to anaesthetic?
  Low Moderate High

- What is your normal physical activity level?
  Low Moderate High

Please describe your average training regime below: (ex: hrs of exercise/week)

- Are you currently taking, any anaesthetics, antiarrhythmic drugs, drugs which may trigger methemoglobin formation or any other medications?
  Yes No

If yes please list them below.
• Have you ever injured either of your ankles/knees/hips?  
  Yes  No  
  If yes please explain the circumstances (which joint (left or right), the severity, how long ago)

• Do you have any allergies?  
  Yes  No  
  If yes, please list them below.

• Do you have any known medical conditions?  
  Yes  No  
  If yes, please list them below.

• Do you have any skin sensitivities?  
  Yes  No  
  If yes, please list them below.

I ___________________ certify that the information given is true, correct and complete to  
(Name of participant)  
the best of my knowledge X ________________________________  
(Signature of participant)
The Effect of Dorsal Foot Anesthesia on Gait Control

CONSENT TO PARTICIPATE IN RESEARCH

You are asked to participate in a research study conducted by Leah Bent, and Erika Howe, from the HHNS at the University of Guelph. This study will provide insight into how information from the skin on the top of the foot contributes to gait and obstacle avoidance. The study will be conducted in the biomechanics lab in the animal and nutritional science building (ANNU), room 273. Please carefully read through the consent form and if you agree to participate in the study, indicate so with a signature.

If you have any questions or concerns about the research, please feel free to contact Leah Bent: the Faculty Supervisor. Contact is listed above.

PURPOSE OF THE STUDY

To investigate the functional relevance of cutaneous receptors on the dorsal surface of the foot during gait and obstacle avoidance under the influence of anesthesia

PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things:

Control Trials: Skin Sensation Intact

You will walk forward at a comfortable and natural pace the length of the set course (5m) with head facing forward and arms at your side while information about body movement is collected from the Optotrak system via infrared markers. To record the foot movement, the marker platform will be E-Z bond glued to the outside surface of your foot. The glue will only be applied after it has been tested on a small area of the palm to ensure no skin sensitivities. It will be easily removed with a de-bonder liquid. All other markers will be secured to the segments using tape.

You will be given practice trials to obtain a ‘standard’ individual walking speed while walking with eyes open. You will perform the following test conditions in a randomized order:

1. No Obstacle
2. Over an Obstacle with Left foot
3. Over an Obstacle with Right foot

**The obstacle will be set up to a height that is 45% of your lower leg length**
For some trials, you will put on “basketball goggles” which remove the bottom half of your visual field. This will take away vision of your environment two steps ahead of you and of your legs while walking. You will perform the same test conditions listed above while wearing the goggles. There will be an opportunity for you to practice walking and stepping over obstacles while wearing the goggles before data collection begins.

**Anesthetized Trials:**

A topical anesthetic (EMLA® cream) will be applied to the surface of the skin of the top of one foot (30cm² area) near the ankle joint. The cream will then be covered with the provided air tight plastic cover. Before the EMLA cream is applied, the region will be shaved to remove any hair since it can reduce the perception accuracy of the skin sensation threshold (how numb you are). The degree of skin sensation will be tested using nylon monofilaments (small probes). With your eyes closed, you will indicate when you can feel the touch. It may take up to an hour for the skin sensation to reach the appropriate level, however the cream will be on the skin for a maximum of 2 hours.

The trial conditions will be repeated with skin sensation reduced. Each condition will be repeated 5 times for a total of 80 trials. Re-evaluation of anesthesia will occur after the test trials to ensure an adequate level of anesthetization (numbness) was maintained.

**POTENTIAL RISKS AND DISCOMFORTS**

Be aware, although unlikely you may experience mild side effects associated with aesthetic including: irritation, redness, slight inflammation, tingling/itchiness to the area of the skin in contact with EMLA® cream. These are normal, temporary reactions and will disappear without treatment or any lasting effects. To reduce the likelihood of a reaction the cream will only be applied to clean, intact skin avoiding areas that are sensitive or broken.

After the application of the EMLA® cream, the effects will remain for at least 1-2 hours. There is a potential risk of injury to this area due to the reduced sensation because you may or may not be able to detect external perturbations to the skin. You will need to remain in the lab until your sensation returns to a 'normal' level. This will likely be around 20-30min after testing is completed.

There is a potential irritation of the skin that can result from the E-Z bond glue. The adhesive will only be used on cleaned and intact skin. A small area on the palm of the hand will be tested first to ensure no side effects will ensue. Once the marker platform is removed (with the de-bonder) the surface of the foot will be washed with soap and warm water to remove any lasting residue.

There is a minor risk of tripping over the obstacle or falling during data collection. It will be ensured that safety precautions are taken – spotters will be there to help catch you if your balance is perturbed.

Minor Risks are associated with the EMG electrodes. There is a potential risk for slight skin irritation with the electrode adhesive. A precautionary measure taken will be to ensure that the areas of the skin where the electrodes will be placed will be cleaned with alcohol swabs before and after testing.
POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY
The Participant may benefit from the knowledge that they have contributed to increasing scientific knowledge; this study will help gain insight into the contributions of information from skin on the top of the foot with respect to gait patterns and could potentially be further applied to rehabilitation procedures.

PAYMENT FOR PARTICIPATION
There will be no payment compensation for the participants in this study.

CONFIDENTIALITY
Every effort will be made to ensure confidentiality of any identifying information that is obtained in connection with this study. The personal information collected in this study will be seen by Erika Howe, and Dr. Leah Bent & exclusively. Results will be reported in scientific publication without identification. All data will be stored in a locked location (office of Dr. Bent) for up to five years, or until the data are published, whichever comes first.

PARTICIPATION AND WITHDRAWAL
You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may exercise the option of removing your data from the study. You may also refuse to answer any questions you don’t want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise that warrant doing so.

RIGHTS OF RESEARCH PARTICIPANTS
You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. This study has been reviewed and received ethics clearance through the University of Guelph Research Ethics Board. If you have questions regarding your rights as a research participant, contact:

Director, Research Ethics
University of Guelph
437 University Centre
Guelph, ON  N1G 2W1

Telephone: (519) 824-4120, ext. 56606
E-mail: sauld@uoguelph.ca
Fax: (519) 821-5236

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I have read the information provided for the study "The Effect of Dorsal Foot Anesthesia on Gait Control" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.
SUBJECTS NEEDED FOR ANESTHESIA GAIT STUDY

You are invited to participate in a study to investigate the neural input regarding ankle joint position sense and its functional relevance during walking. Previous research has demonstrated that receptors in both muscle and skin contribute to our internal sense of position and movement of our joints in space.

We are looking for young healthy subjects between the ages of 18-35 years of age. If you decide to participate, we will be applying a topical anesthetic to the dorsal surface of one foot while recording joint movement and also information from the muscles of the lower leg using surface electrodes. The duration of the experiment is approximately 4 hours or until skin sensation has been restored. If you think you may be interested in participating or would like to find out more information about the study please contact:

Leah Bent or Erika Howe (519) 824-4120 x 52116

Or by email at lbent@uoguelph.ca or howee@uoguelph.ca

This study is being conducted through the Department of Human Health and Nutritional Sciences at the University of Guelph, and has received approval from the University of Guelph Human Research Ethics Board.


Bessou P, Laporte Y (1962) Responses from primary and secondary endings of the same neuromuscular spindle of the tenuissiumus muscle of the cat. In: Barker D (ed) Symposium on Muscle Receptors. Hong Kong University Press, Hong Kong


Elias LJ, Bryden MP, Bulman-Fleming MB (1997) Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia 36:37-43


Goodwin GM, McCloskey DI, Matthews PB (1972) Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? Science 175:1382-1384


MahNS DA, Perkins NM, Sahai V, Robinson L, Rowe MJ. (2006)


Raspovic A Gait characteristics of people with diabetes-related peripheral neuropathy, with and without a history of ulceration. Gait Posture. DOI 10.1016/j.gaitpost.2013.03.009


128


