# Negotiating Varying Ground Terrain during Locomotion: Insights into the Role of Vision and the Effects of Aging

by

Daniel S. Marigold

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Kinesiology
(Behavioural and Cognitive Neuroscience)

Waterloo, Ontario, Canada, 2006

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A THESIS

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## ABSTRACT

We continually encounter different ground terrain such as slippery, compliant, uneven, rocky, and irregular terrain when walking, yet we know very little about how individuals safely negotiate this type of complex environment. Furthermore, we know little about how aging affects stability in these situations despite the increased risk of falls and fall-related injuries among older adults. Paramount to our comprehension of how individuals safely traverse challenging ground terrain is to understand how visual information is utilized as vision is the first line of defense for preparing for and/or avoiding potentially hazardous terrain or obstacles. Thus, the objective of this thesis was to provide a better understanding towards how individuals negotiate different ground terrain in the environment to maintain dynamic stability and prevent the occurrence of a fall. In particular, the role of vision and the effects of aging were investigated. Three studies focused on the role of vision while negotiating varying ground terrain while two studies examined stability across these surfaces. Two main conclusions can be drawn from the results of the three studies on the role of vision. First, regardless of age individuals fixate on highly task-relevant areas (i.e. surfaces eventually stepped on) in an on-line manner and by fixating approximately two steps ahead. Second, visual information from the lower visual field is important for negotiating varying ground terrain. This latter finding has implications for older adults who wear multi-focal glasses and suggests that these individuals should be cautious when wearing these glasses in complex environments. In terms of stability, the results suggest that young and older adults demonstrate greater instability when walking across varying unstable ground terrain compared to solid level ground. Older adults are particularly more unstable in the medial-lateral direction when negotiating the challenging terrain, which may explain the frequency of laterally directed falls and increased hip-fracture risk with advancing age. Interestingly, older adults appear more stable in the anterior-posterior direction; although, this can largely be explained by the cautious gait strategy (i.e. slower walking speed and shorter steps) adopted by these individuals. The results of the studies of my thesis provide valuable insight into how individuals safely negotiate different types of challenging ground terrain when walking. Importantly, this knowledge can serve as an initial step in attempting to reduce falling among those at risk.

**ACKNOWLEDGEMENTS**

I have always been inspired by the following quote: “Somewhere between the base and the summit is the answer to why we climb” (The North Face). I suppose this would be due to my passion for rock climbing. However, it can also be said: “somewhere between the conception of a study and the final published manuscript is the answer to why I do research.” Of course, I would not have been able to accomplish what I have without the help of several people.

I would like to thank my supervisor, Dr. Aftab Patla, and my thesis committee members, Drs. Rich Staines, Jim Frank, Jacques Duysens, and James Danckert. Each has contributed to this work in a different but important way. I would particularly like to acknowledge and thank Dr. Rich Staines for taking on the role of my acting supervisor when he was needed. In addition, I would like to acknowledge and thank Dr. Jacques Duysens for coming all the way from the Netherlands for my defense and for hosting me and my wife in Nijmegen for three months in the summer of 2005. I look forward to continued collaborations.

I would like to thank all of the past and present GaP lab members who were around during my time in Waterloo. Their help was and continues to be greatly appreciated. In addition, I would like to thank my officemates, Janessa and Karen, for our talks on various subjects and for listening to my complaints. I would also like to thank Wendell Prime for building most of the apparatus for my thesis experiments. And I would like to thank Ruth Gooding for always being there to answer my questions and steer me in the right direction.

Throughout my schooling my family has provided me with the love and support I needed. I would like to thank my wife Erica, for being there, my parents Wayne and Pat, for their advice, and my sister Denise and brother-in-law Ian for the stimulating discussions during our regular dinners. Importantly, I would also like to thank my rock climbing partners, Jason and Brodee, for providing me with much needed excursions away from the lab and analyzing data.

Finally, I would like to acknowledge the Canadian Institutes of Health Research for providing me with a Canada Graduate Scholarship, which has supported me financially throughout this endeavor.

## DEDICATION

This thesis is dedicated to two important individuals. First, I would like to dedicate this thesis to my supervisor, my mentor, and my friend, Aftab. He has continually motivated and encouraged me to be the best that I can be and has given me the start to my career that I needed. His wisdom and insight has enabled me to mature as a researcher.

Second, I would like to dedicate this thesis to my wife and my best friend Erica, who has supported me throughout my PhD degree. Her endless love has made it possible to accomplish what I have. And of course, I can't forget the centre of attention, our dog Leila, who I hope understands why I can't play the entire day, every day!

# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF ILLUSTRATIONS

**ABBREVIATIONS**

ANOVA = analysis of variance

AP = anterior-posterior

ARM = age-related maculopathy

COM = centre of mass

CNS = central nervous system

FEF = frontal eye fields

LIP = lateral intraparietal cortex

LVF = lower visual field

ML = medial-lateral

MST = medial superior temporal cortex

MT = middle temporal area

NA = not available

NV = normal vision

OA = older adults

RMS = root-mean-square deviation

SC = superior colliculus

SD = standard deviation

SM = stability margin

VIP = ventral intraparietal cortex

YA = young adults

## ADDITIONAL MANUSCRIPTS

The following is a list of published and submitted manuscripts done during the course of my PhD degree at the University of Waterloo that are not a part of my thesis:

Marigold DS, Patla AE. Adapting locomotion to different surface compliances: neuromuscular responses and changes in movement dynamics. J Neurophysiol 2005; 94: 1733-1750.

Marigold DS, Weerdesteyn V, Patla AE, Duysens J. Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. Exp Brain Res 2007; 176: 32-42.

van der Linden MH, Marigold DS, Gabreëls FJM, Duysens J. Corrective responses to an unexpected support surface height during walking. Part 2: Muscle activations. Submitted.

# CHAPTER 1 – Introduction

## 1.1 Overview of thesis

This thesis begins with the overall objective followed by sections devoted to background research under the following areas: (1) vision and action and (2) dynamic stability during locomotion. The effects of aging are considered under both sections. The end of this chapter details the research questions which will serve to guide this thesis. Subsequent chapters detail the studies, which investigate the research questions.

## 1.2 General objective of the thesis

The objective of this thesis is to provide a better understanding towards how individuals negotiate varying ground terrain in the environment to maintain dynamic stability and prevent the occurrence of a fall. Central to this understanding is how visual information plays a role as the visual system is unique in that it is the only sensory system able to provide information to the central nervous system (CNS) before experiencing the different and potentially hazardous terrain. An additional objective is to better understand how aging affects stability and the utilization of vision in maintaining balance across unstable ground terrain as older adults are at a higher risk for falls.

## 1.3 Background research

Negotiating the outside environment requires the ability to maintain stability during locomotion on different ground terrain such as uneven, irregular, compliant, rocky, or slippery surfaces. A multitude of sensory information bombards the nervous system as an individual traverses this terrain. In order to safely negotiate varying ground terrain, which is typically experienced while ambulating outside, one must acquire details of the environment. This may include any potential obstacles or characteristics of potentially threatening surfaces. When stepping on challenging terrain stability may be compromised and require proactive and/or reactive balance strategies evoked by the CNS to prevent a fall and/or fall-related injury. Visual information is unique in that it can act as a first line of defense for upcoming stability issues and provides the brain with necessary environmental information. Therefore, it is important to understand how visual information is utilized to negotiate complex environments consisting of varying ground terrain and to investigate how stability is affected.

Older adults show deteriorating balance and mobility and the incidence of falling in this population is very high (Berg et al. 1997; Blake et al. 1988; Campbell et al. 1999; Tinetti et al. 1988). Furthermore, visual function is often diminished in older adults and thus, in a task relying on visual input stability may be altered to a greater extent. Consequently, it is imperative that we better understand how aging influences the ability to negotiate varying ground terrain (both in terms of the use of vision and how stability is compromised) so that falls can be reduced and the burden on the health care system from fall-related injuries can be alleviated.

### 1.3.1 Vision and action

In normally sighted individuals vision is overwhelmingly involved in our daily lives. Vision provides the CNS with a multitude of information that facilitates action and allows us to interact with our environment. Goodale and Humphrey (1998) remark: "…vision evolved in animals, not to enable them to 'see' the world, but to guide their movements through it." Therefore, it is only fitting to begin our understanding of how humans negotiate different ground terrain in complex environments by first delving into the role of vision in this context. Studies of eye movements in natural behaviour have proven to be extremely useful in understanding the role of vision (Findlay and Gilchrist 2003; Hayhoe and Ballard 2005; Land 2006) and thus, we commence here.

#### 1.3.1.1 Role of vision and eye movements in the control of daily activities

Studies have investigated eye movements across a range of tasks including driving (Land 1992; Land and Lee 1994; Land and Horwood 1995; Land and Tatler 2001; Marple-Horvat et al. 2005), tea-making (Land et al. 1999; Land and Hayhoe 2001), sandwich-making

(Hayhoe 2000; Hayhoe et al. 2003; Land and Hayhoe 2001), hand washing (Pelz and Canosa 2001), object manipulation (Johansson et al. 2001), object-sorting tasks (Triesch et al. 2003), block-copying tasks (Ballard et al. 1992), model-copying tasks (Aivar et al. 2005), playing cricket (Land and McLeod 2000), playing chess (Charness et al. 2001; Reingold et al. 2001), studying paintings (Yarbus 1967), simple walking tasks (Hollands et al. 1995; Hollands et al. 2002; Patla and Vickers 2003), obstacle avoidance (Di Fabio et al. 2003a,b; Marigold et al. 2007; Patla and Vickers 1997), finding a door in a hallway (Turano et al. 2003), and crossing an intersection (Geruschat et al. 2003). A dominant finding among these studies is that people fixate on predominantly task-relevant areas (Geruschat et al. 2003; Hayhoe 2000; Hayhoe et al. 2003; Johansson et al. 2001; Land 2006; Land and Lee 1994; Land et al. 1999; Land and McLeod 2000; Land and Hayhoe 2001; Pelz and Canosa 2001). For example, people fixate the jar of jam, a knife, and the bread for sandwich-making (Hayhoe 2000; Hayhoe et al. 2003; Land and Hayhoe 2001), the kettle and cup for tea-making (Land et al. 1999; Land and Hayhoe 2001), and the soap dispenser and faucet for hand-washing (Pelz and Canosa 2001). Furthermore, when crossing an intersection people fixate on crossing elements such as the curb and crosswalk lines while approaching and during crossing and fixate on the cars when waiting at the curb (Geruschat et al. 2003).

Expanding on the idea of task-relevant fixations many studies have shown how critical landmarks/anchors are important for guiding future actions (Johansson et al. 2001; Land and Lee 1994; Land and McLeod 2000). This idea of a visual anchoring behaviour has been suggested by Johansson et al. (2001) for an object manipulation task in which they found most fixations were directed to specific landmarks important for successful completion of the task. Land and Lee (1994) showed that drivers saccade to and fixate the tangent point (inside bend) of a curved road before and during the turn. This visual input provides information regarding the curvature of the road and is highly important for good performance. In fact, when eye movements are restricted driving performance is impaired (Marple-Horvat et al. 2005), further substantiating the importance of eye movements in visually guided tasks.

There have been relatively few studies investigating eye movements (although several studies have looked at vision) during walking. This is somewhat surprising as this task is certainly highly visual in nature. In an early study by Hollands et al. (1995) examining horizontal eye movements, they found that people make saccadic eye movements directed to the upcoming stepping target just prior to foot liftoff from the present step target. In contrast, Patla and Vickers (2003) have found that individuals fixate on specific targets in the travel path that are located two steps ahead when walking. Dominant gaze behaviour during walking seems to be one which involves the "eyes parked in the front of the moving observer and being carried along by the observer" (Patla 2004), also referred to as travel gaze fixation (Patla and Vickers 1997, 2003). This type of gaze behaviour is also found in cats when walking in a cluttered environment (Fowler and Sherk 2003).

Studies on obstacle avoidance during walking show that visual fixations are commonly directed to the obstacle during the approach phase (Patla and Vickers 1997) and downward saccades are made to an area behind the obstacle following a cue as to which limb to initiate the step over the obstacle (Di Fabio et al. 2003a). However, peripheral vision is sufficient while stepping over the obstacle as fixations are directed to the landing area (Patla and Vickers 1997) or upward saccades are made to adjust gaze to a forward looking direction (Di Fabio et al. 2003a) and not the obstacle during the cross-over phase. Additionally, gaze is not re-directed to an obstacle suddenly dropped on a moving treadmill when fixating a target two steps ahead (Marigold et al. 2007).

In addition to recording eye movements during stepping to targets and over obstacles, Hollands et al. (2002) investigated fixation patterns during a change in direction of walking. Gaze was aligned with features in the current plane of progression prior to and after the initiation of a transition stride for a change in direction (range of 67 to 92 % of total fixation time) for both cued and advance knowledge trials (Hollands et al. 2002). In addition, saccades were frequently made to the end-point of the new travel path prior to a direction change.

In an environment with many salient features, such as varying ground terrain and obstacles, we would expect fixations to be even more important and to show what visual features are critical to the task. However, no studies have investigated an environment like this and as such eye movement data does not exist. Before going any further, it is important to understand where visual information travels once past the retina and how saccades are generated to fixate on a new location of interest. Therefore, the sections below briefly explain the pathways in which visual information travels from the retina to relevant cortical areas and the neuronal connectivity for controlling eye movements to capture salient visual input.

#### 1.3.1.2 Visual pathways

While we know a great deal about the visual system, for the purposes of this thesis we will only briefly discuss the ‘two visual systems’ hypothesis (Milner and Goodale 1995) as it relates to the present work, in particular, how vision and action are coupled. Visual input enters the retina and projects to either the superior colliculus (SC) in the midbrain or to the lateral geniculate nucleus (LGN) and on to the primary visual area (also known as the striate cortex or V1) (Milner and Goodale 1995; Wurtz and Kandel 2000). From V1, visual input progresses along two different streams: the ventral and dorsal stream visual pathways (Milner and Goodale 1995; Ungerleider and Mishkin 1982). Visual input travels ventrally to the inferotemporal cortex via area V4 and forms the ventral stream pathway (Kandel and Wurtz 2000; Milner and Goodale 1995). In contrast, in the dorsal stream pathway visual input travels from V1 dorsally to the posterior parietal cortex through the middle temporal area (MT) (Kandel and Wurtz 2000; Milner and Goodale 1995).

Ungerleider and Mishkin (1982) proposed that the dorsal stream was the ‘where’ pathway important for spatial vision whereas the ventral stream was the ‘what’ pathway important for object vision. More recently, however, Milner and Goodale (1995) have proposed that the distinction of the two visual streams has more to do with the output. Thus, they envision the dorsal visual stream as playing a role in visually guided action whereas the ventral stream mediates visual perception or recognition (Milner and Goodale 1995). This is supported, in part, by studies with a patient, D.F., who has a form of visual agnosia (due to damage in the lateral portions of the occipital lobes of the cortex) and who can carry out visuo-spatial tasks but is impaired in recognition (Milner and Goodale 1995). For example, she is able to reach out and put cards into differently oriented slots but is severely impaired in the ability to perceptually report the orientation of the slot. Moreover, she can reach and grasp objects of different sizes but cannot discriminate them perceptually. In an obstacle avoidance task during locomotion, D.F. was able to maintain proper toe elevation over different obstacle heights similar to controls but the slopes of the line relating verbally estimated or raising one leg while standing close to the obstacle and actual obstacle height was much shallower than controls (Patla and Goodale 1996). In a task relying on vision for safe foot placement the dorsal stream may be particularly active.

#### 1.3.1.3 Neuronal circuitry involved in the generation of saccadic eye movements and visual fixations

The neuronal circuitry involved in the generation of saccadic eye movements and visual fixations is housed throughout the cortex and brainstem. Most of our understanding of this control is through experimentation with non-human primates. Saccades occur at speeds up to 900°/s (Goldberg 2000) and serve to shift the region of the retina with the highest visual acuity, the fovea, onto the image of interest. The foveal region extends out to an angle of eccentricity of 1° and the parafoveal region from 1° to 5° with the peripheral region extending out to the remainder of the visual field (Findlay and Gilchrist 2003).

The motor signals driving the ocular muscles controlling saccades are organized in the brainstem. Specifically, the horizontal component of a saccade is organized in the paramedian pontine reticular formation and rostral medulla whereas the vertical component is organized in the mesencephalic reticular formation (Goldberg 2000). However, higher centres are usually involved in the decision to make a saccade. The parietal cortex (particularly the lateral intraparietal area, or LIP), frontal eye fields (FEF), and SC are paramount in directing eye movements. Furthermore, each area is reciprocally connected to each other and a variety of other visual and non-visual areas. For example, the FEF reciprocally connects with posterior visual areas including V2, V3, V4, MT, MST (medial superior temporal cortex), and the LIP (Moore et al. 2003). In addition, LIP projects to the parahippocampal gyrus (for spatial memory), FEF, and SC (Colby and Goldberg 1999).

Neurons in the LIP are thought to encode a spatial representation for the space explored by eye movements (Colby and Goldberg 1999). LIP neurons are active when a stimulus (or target) is salient (Gottlieb et al. 1998). As such, LIP neurons are not so much involved directly in the planning of saccades, but rather act as a salience map and facilitate the selection of possible targets (Colby and Goldberg 1999; Findlay and Gilchrist 2003;

Gottlieb et al. 1998). The human homologue of LIP may be in the superior parietal cortex, adjacent to the medial end of the intraparietal sulcus (Sereno et al. 2001). The FEF can also be regarded as a salience map where the topographic locations of targets of interest are recorded and the activation of this map guides eye movements (Findlay and Gilchrist 2003; Schall and Hanes 1998; Schall 2002). It is involved in both covert and overt gaze shifts (Schall and Hanes 1998; Schall 2002).

The SC is critically important in integrating information from a variety of areas including the FEF and LIP and sending signals to the reticular formation to elicit eye movements. Electrical stimulation of the SC in primates produces orienting responses that involve the coordination of the eyes, head, and body (Sparks 1999). Two types of neurons within the SC are particularly relevant for saccade generation and visual fixation. Saccade neurons are neurons that discharge before and during saccades and are located throughout the intermediate layers of the SC (Munoz and Istvan 1998). On the other hand, fixation neurons are neurons that are tonically active during a visual fixation and pause during saccades and are located in the rostrolateral pole of the SC (Munoz and Istvan 1998). Munoz and Istvan (1998) argue that local inhibitory interneurons shape the reciprocal discharge patterns of fixation and saccade neurons for saccade generation and fixation duration. This is from observations that microstimulation in monkeys of the rostral SC adjacent to fixation neurons results in short-latency inhibition of saccade neurons whereas stimulation of the caudal SC adjacent to saccade neurons leads to short-latency inhibition of both fixation neurons and saccade neurons distant from the stimulation site.

It is important to note that other areas including the supplementary eye fields, thalamus, basal ganglia, cerebellum, and dorsolateral prefrontal cortex are also important in saccade generation and suppression (Munoz 2002, Pierrot-Deseilligny et al. 1991, Schall 2002) but a detailed discussion on these structures is beyond the scope of this review.

#### 1.3.1.4 Visual control of locomotion

Visual input provides details of the environment and information regarding self-motion. It is the only sensory system able to provide critical information for successful locomotion at a distance. Visual information is essential for implementing avoidance strategies, for making proactive adjustments to accommodate different ground terrain, and for navigation when the goal is both present and absent (Patla 1997).

Optic flow, the pattern of visual motion across the retina, is produced as one moves in the environment with the focus of expansion corresponding to the heading direction (Gibson 1950; Turano et al. 2005; Warren et al. 2001). Optic flow need not be sampled continuously; rather 200 ms of visual input every stride (which is normally around 800-1200 ms) is enough to acquire self-motion information via optic flow to, for example, maintain centre of mass position on a treadmill (Patla 1997, 1998). Warren et al. (2001) have recently found support for the idea that walking to a goal can be achieved by keeping the focus of expansion in the direction of the goal. These authors showed by manipulating the optic flow in an immersive virtual environment individuals utilize a combination of optic flow and perceived direction of the goal (an egocentric-direction strategy which minimizes the distance between the goal and self) to guide walking. When optic flow is eliminated, an egocentric-direction strategy can compensate (Turano et al. 2005; Warren et al. 2001). Recently, Schubert et al. (2003) have argued that while the focus of expansion is useful for determining heading direction it is not the dominant cue and that motion parallax may also be important. When a goal is not readily seen, individuals can use landmarks to navigate through an environment (Foo et al. 2005; Turano et al. 2005). Research with monkeys has demonstrated that the ventral intraparietal area (VIP) is important for encoding optic flow and heading information (Bremmer et al. 2002; Gabel et al. 2002; Schaafsma and Duysens 1996; Schaafsma et al. 1997; Zhang and Britten 2004).

In a series of experiments, Sherk and Fowler (Sherk and Fowler 2001; Fowler and Sherk 2003) investigated visual control of locomotion in the cat in an attempt to better understand the use of optic flow for guiding movement. Errors during locomotion in a cluttered environment where the task was to avoid a series of obstacles were significantly increased under low-frequency strobe lighting conditions where motion cues were essentially eliminated compared to normal vision conditions (Sherk and Fowler 2001). This suggests that motion-sensitive neurons are normally used to guide foot placement during locomotion (Sherk and Fowler 2001). In a similar task, Fowler and Sherk (2003) found the most common gaze event for locomoting cats was the constant gaze episode, where the cat had a downward gaze angle and which consumed approximately 60% of each trial. It was subsequently hypothesized that during these constant gaze episodes the pattern of retinal motion was similar to Gibson's optic flow field and the cats were acquiring critical visual information during these intervals (Fowler and Sherk 2003). Thus, these studies support the notion of optic flow being used to guide locomotion, even under challenging conditions such as walking in a cluttered environment.

Studies on the visual control of locomotion have also shown when and how visual information is used to guide foot placement. Obstacle avoidance strategies and step length changes can be implemented with a visual cue present one step before while steering changes require an additional step (Patla et al. 1989; Patla et al. 1991; Patla 1997). As mentioned earlier, travel fixation, where the eyes are parked in front of the body and carried along, is the most dominant form of fixation while approaching and crossing over an obstacle and when targeting specific areas to step (Patla and Vickers 1997, 2003). Interestingly, travel fixations, which are akin to the common gaze episodes in cats and thought to be a time when the individual acquires optic flow information, are virtually non-existent when negotiating varying ground terrain (see Chapter 3). Rather, active visual scanning of task-relevant features of the environment becomes more critical.

Visual information need not be sampled continuously though. Intermittent visual sampling of the environment is adequate for safe travel as demonstrated by the findings that sampling occurs for less than 10 % of the travel time when foot placement location is not restricted to just over 30 % when it is (Patla et al. 1996; Patla 1997). These findings suggest that as the terrain difficulty increases so does the need for visual sampling (visual sampling is increased by the number of samples rather than duration). Both steering and obstacle avoidance dramatically increase the need to sample vision (Patla et al. 1996). Visual sampling is modulated such that during the approach phase, prior to crossing an obstacle, sampling increases as obstacle height increases (Patla et al. 1996; Patla 1997). However, sampling is unaffected during the crossover step suggesting that exteroceptive information about the environment is used in a feedforward manner (Patla et al. 1996; Patla 1997).

Through a variety of studies it has been argued that visual information regarding the environment is used in a feedforward manner. One experimental paradigm that lends support to this idea involves stepping over obstacles in the travel path. Specifically, visual information obtained during the approach phase is utilized to pre-plan the step over an obstacle (Mohagheghi et al. 2004; Patla et al. 1996; Patla 1997; Patla and Vickers 1997). During an obstacle avoidance task, fixations are made to the obstacle predominantly during the approach phase rather than during the step over the obstacle and the frequency of fixations are increased with increasing obstacle height (Patla and Vickers 1997). Although lead and trail limb toe clearance over an obstacle is increased when vision during the approach phase is occluded, initial dynamic visual sampling of three steps before vision is removed allows for successful avoidance (Mohagheghi et al. 2004). In addition, occlusion of vision during the crossing over phase has no effect on clearance measures (Mohagheghi et al. 2004). Thus, the findings from this study in conjunction with the observations that fixations are not made to the obstacle during the crossover step (only during the approach phase) and visual sampling during this step is not modulated based on obstacle height provide ample evidence to suggest visual information regarding an upcoming obstacle is sampled in a feedforward control mode (Mohagheghi et al. 2004; Patla et al. 1996; Patla and Vickers 1997).

Studies manipulating binocular vision during obstacle avoidance provide additional support for feedforward control. Toe clearance is increased under monocular visual conditions compared to binocular conditions for obstacle avoidance (Patla et al. 2002). Toe clearance is not affected under monocular vision during the step over the obstacle suggesting binocular vision is not necessary during this phase and that binocular vision is used during the approach in a feedforward manner (Patla et al. 2002). Toe clearance is also increased when only monocular vision is available during the approach phase even if binocular vision is available during the step over the obstacle (Patla et al. 2002).

Visual information during the approach phase may be used to judge distance to the obstacle. Interestingly, the ground terrain may influence this judgement. Distance judgement is impaired when the vertical field of view is reduced rather than the horizontal field of view suggesting the importance of near-ground information (Wu et al. 2004). However, distance judgement is only accurate when the near-ground surface is scanned prior to the far-ground surface and not the reverse direction (Wu et al. 2004). Consequently, Wu et al. (2004) argue that accurate distance judgement requires surface integration of local patches of the ground to form a global ground surface representation.

Visual information is also used in a feedforward manner while stepping onto specific targets. Patla and Vickers (2003) have shown that individuals fixate a footfall target approximately two steps (or 800-1000 ms) ahead. Interestingly, cats can walk without error (i.e. stepping in large holes along a path) for up to four steps when vision is removed suggesting that visual information is acquired well in advance to plan additional steps (Wilkinson and Sherk 2005). In contrast, Hollands and colleagues have shown that individuals fixate (through horizontal saccadic eye movements) the next target footfall just prior to every step (i.e. during end of stance) (Hollands et al. 1995; Hollands and Marple-Horvat 1996, 2001). This pattern is unaffected when ambient lighting is eliminated and the irregularly placed targets are lit by light emitting diodes (LEDs) (Hollands and Marple-Horvat 1996). When the LEDs were temporarily turned off at irregular intervals very few steps were affected (as demonstrated by only an increase in stance duration in some trials) suggesting that continuous visual information is not necessary for successful and accurate stepping (Hollands and Marple-Horvat 1996). To determine the robustness of the timing between saccades and stepping, Hollands and Marple-Horvat (2001) manipulated visual information (no vision manipulation, no vision of targets during stance phase preceding foot-lift, vision during stance phase preceding foot-lift, and vision present during stance after 500 ms of no vision) during a task which required precision stepping onto targets. The mean interval between saccade onset and ipsilateral foot-lift did not differ between visual conditions; however, the interval between saccade onset away from the target and contralateral footfall on that target did vary across visual conditions (which argues against the need for visual feedback towards the end of the step) (Hollands and Marple-Horvat 2001). These results support the notion of coordination between the oculomotor and stepping motor control systems and further support the idea of visual information being used in a feedforward control manner for the next step rather than for feedback guidance of the current step (Hollands and Marple-Horvat 2001). Although there are differences between these findings and those of Patla and Vickers (2003) and Wilkinson and Sherk (2005), the interpretation that visual information seems to be used in a feedforward manner to control stepping to targets remains clear.

When approaching varying ground terrain, fixations are made to areas eventually stepped on and the frequency of fixations to the different surfaces during the approach phase is far greater than while on the surfaces (see Chapter 3). Thus, information acquired during the approach to challenging ground terrain allows the CNS to obtain valuable insight into environmental details to plan foot placement and hence, the path to walk.

While visual information may be used in a feedforward manner during the approach to an obstacle and for stepping to specific targets, visual information (i.e. exproprioceptive information) is sampled on-line to fine-tune the swing limb trajectory during the step over an obstacle (Patla 1997, 1998; Rietdyk and Rhea 2006). On-line visual control implies the use of visual information sampled as the person is walking, which is used to guide or alter a current movement (i.e. feedback control). However, the time lag between the sampled visual input and its use in manipulating action (e.g. foot placement) may vary and thus may be considered more feedforward control. Thus, on-line visual control entails both feedback and feedforward mechanisms to guide action. Sampling visual information two steps in advance (seen in Patla and Vickers 2003 and Marigold and Patla 2007) provides detailed information useful for foot placement, which may be used to adjust the current or subsequent step.

Evidence for on-line visual control stems from the findings of smaller toe clearance variability of the lead limb compared to the trail limb during obstacle avoidance (Patla 1997). Additionally, when vision of the lead limb is blocked by peripheral blinders attached to glasses frames such that an obstacle is present until the last step before it and vision of the limb during swing is occluded, toe clearance, variability in toe clearance, and toe position before the obstacle at toe-off are all increased (Patla 1998; Rietdyk and Rhea 2006). Rietdyk and Rhea (2006) also demonstrated that visual exproprioception (i.e. visual information regarding the position of one's limbs relative to the environment) of the lower limbs is important for lead limb toe clearance but not foot placement prior to obstacle crossing whereas exproprioceptive information regarding obstacle position is important for foot placement prior to obstacle crossing and for trail limb toe clearance. When binocular vision is removed during the step over the obstacle, the CNS compensates with a head turn to the direction of the occluded eye (yaw direction) to re-direct the visual field and ensure a safe foot trajectory over the obstacle (Patla et al. 2002). Thus, visual information is used both in a feedforward and feedback control mode depending on the task and/or situation. Recently, Patla and Greig (2006) have argued that vision is not only used in a feedforward manner in the approach phase to obtain obstacle characteristics but on-line visual control during this phase is also used to guide foot placement, particularly just prior to stepping over an obstacle. Additionally, Reynolds and Day (2005) illustrated the importance of visual feedback on the accuracy of foot placement while stepping. Here, occlusion of vision at the point of foot-lift resulted in greater error in placement.

While we have begun to understand how vision is used to step over obstacles and onto targets, little, if any, is known about how visual information is used and acquired in more realistic situations such as negotiating an environment with varying ground terrain. This is somewhat surprising given the frequency with which one encounters this type of situation on a daily basis.

#### 1.3.1.5 Considerations of aging on vision

Older adults have impaired contrast sensitivity, binocular visual acuity, colour discrimination, dark adaptation, depth perception, and reduced useful field of view compared to young adults (Black and Wood 2005; Haegerstrom-Portney et al. 1999; Owsley et al. 1995; Sekuler et al. 2000; Watson 2001). Declines in visual function are associated with deficits in physical functioning in older adults (West et al. 2002). In older women with declining visual acuity, fall risk is significantly increased (Coleman et al. 2004). In older adults, loss of the visual field is associated with slower gait speed and increased number of bumps into objects on a mobility course (Turano et al. 2004). In addition, decreased contrast sensitivity and stereopsis are associated with increased postural sway in older adults when standing on challenging terrain (Lord and Menz 2000). While walking, older adults' range of eye movements are larger, faster, and more frequent than young adults with their viewing point below eye level (Itoh and Fukuda 2002).

Cataracts, glaucoma, and age-related maculopathy (ARM) are all common problems associated with aging (Watson 2001) and can severely limit visual function and greatly affect activities of daily living. In fact, the risk of falling is increased in individuals with these conditions (Black and Wood 2005; Harwood 2001; Lord and Dayhew 2001; Tinetti et al. 1988). Toe clearance and toe elevation variability are increased during obstacle avoidance in persons with cataracts, especially with low-lying obstacles (Patla 1997).

Individuals with ARM and glaucoma are less likely to make head movements that maximize safety while crossing an intersection compared to fully sighted individuals (Hassan et al. 2005). In particular, these individuals exhibit a lower frequency of head turns, which may suggest a greater amount of time is required to acquire visual information for these visually impaired persons. Individuals with ARM also walk slower and with more caution compared to normally sighted individuals (Spaulding et al. 1995) and demonstrate increased toe clearance over low contrast obstacles (Patla 1997).

Corrective lenses are common among older adults and older adults who wear multi-focal glasses (bifocal, trifocal, or progressive lenses) are more impaired with distant depth perception and edge-contrast sensitivity and are twice as likely to fall (as recorded over one year) compared to older adults who do not wear multi-focal glasses (Lord et al. 2002; Lord 2006). When vision is blurred by light scattering lenses (which reduces contrast sensitivity to that of a dense cataract), older adults alter how they step down from a stair (Buckley et al. 2005a,b; Heasley et al. 2005). Specifically, step execution time is increased and more weight is supported by the contralateral (non-stepping) limb (Buckley et al. 2005a). In addition, medial-lateral (ML) stability is compromised as evident from an increased ML ground reaction force impulse during double support prior to foot-lift, reduced distance between the ML centre of mass and centre of pressure, and increased root-mean-square ML centre of pressure while in single support during the step (Buckley et al. 2005b; Heasley et al. 2005).

A recent study on gaze patterns during stepping suggests that older adults look earlier to targets and spend a greater amount of time fixating them than young adults (Chapman and Hollands 2005). In addition, older adults fixate downward longer than young adults before stepping over an obstacle (Di Fabio et al. 2003a). Furthermore, downward saccade frequency is reduced in high-risk cognitively challenged older adults while stepping over an obstacle (Di Fabio et al. 2005). In tasks that require visual input for safe foot placement, such as when negotiating varying ground terrain, older adults may therefore have more difficulty and demonstrate greater instability. Further, the way in which older adults may acquire visual information from the environment may differ compared to young individuals with normal vision. Nonetheless, little is known about the use of vision among older adults in these contexts.

### 1.3.2 Dynamic stability during locomotion: insights from gait perturbation studies

#### 1.3.2.1 Stability during locomotion in young adults

An understanding of how the CNS deals with changes in ground terrain that compromise balance during locomotion is critically important as we are continuously faced with such situations in everyday life. Fundamental to locomotion across unstable terrain is maintaining dynamic stability. Dynamic stability entails controlling the body's centre of mass (COM) within a moving base of support and requires effective proactive and reactive recovery response strategies when exposed to perturbations during locomotion (Marigold and Patla 2002; Patla 2003). As the COM is only within the base of support for 20% of a stride (i.e. during the double support phases), walking is akin to continually recovering from a fall (Patla 2003; Winter 2005). Reactive response strategies rely on sensory information related to unexpected perturbations (Patla 2003). In contrast, proactive response strategies entail both predictive (estimation of expected perturbation based on past experience) and anticipatory (identification of potential perturbation based on primarily visual input and guided by past experience) components (Patla 2003). As aging can have devastating consequences on balance, particularly when encountering unstable terrain, it is crucial that we form some sort of knowledge base on how young, healthy individuals cope in these situations.

Recently, there has been a rapid increase in the number of studies published on recovery responses and balance control on unstable terrain. Investigators have begun to unravel the complex responses to perturbations evoked by slippery surfaces, trips, and irregular and compliant terrain. The most extensively studied of this group is the response to a slippery surface. The recovery response to a slip is quite rapid with muscle activation of the lower limbs between 90 and 200 ms (Marigold and Patla 2002; Marigold et al. 2003; Tang et al. 1998). The perturbed limb responds to the first slip with a flexor synergy to lower the body and increase stability as reflected by muscle sequencing (Marigold and Patla 2002) and a knee flexor moment (Cham and Redfern 2001; Ferber et al. 2002). Ferber et al. (2002) argue that the recovery response serves to maintain the overall support moment during the stance phase. Interestingly, individuals frequently display a lowering (or extensor) strategy of the unperturbed (or swing) limb in response to the first slip during locomotion (Marigold et al. 2003; Marigold and Patla 2002). This lowering strategy is characterized by a decrease in velocity of the horizontal limb trajectory and a rapid extension and lowering of the limb to make contact with the ground (Marigold et al. 2003; Marigold and Patla 2002). While some individuals allow both limbs to make contact with the slippery surface, others demonstrate a toe-touch response in that the unperturbed limb makes brief contact with stable ground adjacent to the slippery surface before continuing its forward trajectory. In either case, the contact of the limb with the ground establishes a larger base of support to increase the stability of the body and prevent the occurrence of a fall. Foot contact with the slippery surface causes the limb to slide forward and the trunk to fall backwards. As a result, an arm elevation strategy is frequently seen in response to the first slip (Marigold et al. 2003; Marigold and Patla 2002; Tang and Woollacott 1999; You et al. 2001). Deltoid muscle activity is observed at approximately 140-150 ms after foot contact on the slippery surface, which nicely corresponds to the later change in arm trajectory (Marigold et al. 2003). The arm elevation strategy is characterized by a rapid increase in velocity to elevate both arms upward and forward and serves to counteract the backward induced trunk motion caused by the slip (Marigold et al. 2003; Marigold and Patla 2002). Reaching and grasping strategies are frequently observed following perturbations to balance (Maki and McIlroy 1997, 2006). An arm elevation strategy is also seen during gait termination on a slippery surface and serves to effectively dissipate the forward COM momentum (Oates et al. 2005). In addition, arm responses occur following waist pull perturbations during gait (Misiaszek 2003) and leg muscle activity is increased when the arms are restricted (Misiaszek and Krauss 2005).

Factors that distinguish between those who fall and those who do not following a slip include an increased displacement of the slipping foot (Brady et al. 2000) and shorter double support phase while on the slippery surface (You et al. 2001). To ensure safe forward progression, there are two critical points during an encounter with a slippery surface: stepping onto the surface and stepping off the surface. Marigold and colleagues (Marigold et al. 2003; Marigold and Patla 2002) have found individuals decrease their rate of loading on the slippery surface as evident from the time to peak of the vertical ground reaction force measured by a force plate under the surface. This may allow the COM to remain positioned over the contralateral limb (i.e. the unperturbed trailing limb) for a longer time to ensure sufficient stability. The push-off phase consists of a decrease in the acceleration impulse (determined from the horizontal ground reaction force along the slippery surface) and a reduction in the unloading impulse (determined from the vertical ground reaction force on the slippery surface) (Marigold and Patla 2002). This strategy is consistent with the notion that large propulsive forces on a slippery surface would further increase the risk of a fall and/or would disrupt the recovery response. Interestingly, faster walking speed (and hence faster COM velocity at slip onset) increases stability when stepping on an unexpected slippery surface despite the advantage of a more anteriorly positioned COM at slip onset with shorter step length when walking slower (Bhatt et al. 2005).

The ability of the CNS to adapt to repeated perturbations is an essential quality that allows us to maneuver in an ever changing environment. Individuals clearly adapt to repeated exposures to unexpected slippery surfaces (Bhatt et al. 2006a,b; Marigold et al. 2003; Marigold and Patla 2002). In fact, this adaptation can last for months after initial testing (Bhatt et al. 2006b). The magnitude of muscle activity (between 120 and 200 ms after foot contact on the slippery surface) decreases after the first slip trial for the perturbed limb tibialis anterior, biceps femoris, and gastrocnemius muscles (Marigold and Patla 2002). The magnitude of the muscle activity for the unperturbed limb rectus femoris, tibialis anterior, and biceps femoris muscles are attenuated after the fourth, third, and second slip trials, respectively (Marigold et al. 2003). The most noticeable adaptation of the recovery response is the diminished arm elevation strategy and the lack of a toe-touch response after the first slip perturbation (Marigold et al. 2003; Marigold and Patla 2002). Changes in COM position relative to the base of support, foot angles, and braking impulse are all used to reduce the perturbation magnitude following the first slip (Bhatt et al. 2006; Cham and Redfern 2002; Marigold and Patla 2002).

The nervous system allows us to utilize knowledge of a situation to shape our subsequent responses. Individuals adopt a more cautious strategy for walking on a slippery surface when they are aware that a slip will occur (Cham and Redfern 2002; Heiden et al. 2006; Marigold and Patla 2002; Siegmund et al. 2006). For example, foot angle is reduced so that contact on the slippery surface is made with a flat foot (Cham and Redfern 2002; Marigold and Patla 2002) and the COM is positioned over the unperturbed limb, which is more stable than the limb in contact with the slippery surface (Marigold and Patla 2002). In addition, individuals often display a 'surfing' strategy whereby they hold their arms forward and outward slightly while their unperturbed limb delays landing and their perturbed limb slides on the slippery surface (Bhatt et al. 2006a; Marigold and Patla 2002). Thus, depending on the context of the situation, the recovery response can be modified to suit the body's need for stability during locomotion on a slippery surface. Heiden et al. (2006) have recently argued that prior slip experience alters gait and the recovery response to a greater extent than actual awareness of a slippery surface. Further, the perceived level of threat of an upcoming surface can alter behaviour. This is nicely demonstrated when an individual stands at the edge of an elevated platform (Adkin et al. 2002; Carpenter et al. 1999).

What is clear from the studies on slipping is the fact that the whole body is involved in the recovery response. Recovery responses to other types of challenging surfaces also demonstrate coordinated whole-body responses (MacLellan and Patla 2006a,b; Marigold and Patla 2005; Misiaszek 2003). Muscle activation of the lower extremities occurs between 97 and 175 ms following stepping on an unexpected compliant surface and activity is modulated while in contact with the unstable surface (Marigold and Patla 2005). Specifically, ankle muscles are active early to stabilize the ankle joint. Furthermore, the knee musculature is modulated such that it facilitates knee flexion (as evident from the observation that knee flexion increases with increasing compliance) to step off the compliant surface and avoid the induced obstacle (by maintaining toe clearance) created by ground depression (Marigold and Patla 2005). MacLellan and Patla (2006a) have recently examined multiple steps on compliant terrain and the transition from a solid to a compliant surface in young adults. Toe clearance after each step was increased and step width and length increased when walking on the compliant surface compared to solid ground. Trunk pitch forward is also increased when walking on compliant terrain (MacLellan and Patla 2006a; Marigold and Patla 2005).

Stepping onto an unexpected ankle inverting platform during walking on a treadmill leads to short-latency (~40 ms) and long-latency (after 100 ms) responses in a range of muscles (Nieuwenhuijzen et al. 2002). In addition, whole-body responses are present as evident from kinematic data and in particular, from a lateral shift of the knee to decrease ankle inversion (Nieuwenhuijzen and Duysens 2005). On irregular terrain, although young adults can adapt to walking, they do so more slowly with longer stride length and increased pelvic acceleration than when on stable terrain (Menz et al. 2003b). Interestingly, head acceleration doesn't change and it has been argued that this is because head movement is tightly controlled to preserve stability of visual information (Menz et al. 2003b).

Tripping can occur when an obstacle is unexpectedly presented or foot elevation is not sufficient to clear the obstacle. We encounter many obstacles daily including a curb or staircase. Recovery responses following tripping demonstrate two very specific phase-dependent strategies: an elevation strategy (Eng et al. 1994; Schillings et al. 1996, 2000) after early swing phase perturbations and a lowering strategy (Eng et al. 1994; Schillings et al. 2000) after late swing phase perturbations. Specifically, muscle activity of biceps femoris and tibialis anterior facilitates elevation (reflected in increased knee flexion) while rectus femoris and biceps femoris controls knee extension involved in the lowering strategy in the onset latency range between 60 and 140 ms (Eng et al. 1994; Schillings et al. 1996, 2000). Additional studies by Schillings et al. (1999) also demonstrated short-latency reflexes around 35 - 40 ms in the lower extremities. These behavioural strategies seem to be dependent on the muscle activity between 110 – 160 ms, rather than on earlier initial reflex responses occurring in less than 100 ms (Schillings et al. 2000). The magnitude of muscle activity has also been shown to vary with the level of perceived threat (uni- vs. tri-limb support) (Rietdyk and Patla 1998). In addition, lowering strategies following trips require the greatest changes in energy and a greater number of recovery steps to regain balance (Forner Cordero et al. 2005).

While these initial studies on tripping responses provided valuable insight, they were restricted mainly to the perturbed swing limb. Recently, Pijnappels and colleagues (Pijnappels et al. 2004, 2005a,b,c) have illustrated the importance of the unperturbed stance limb (i.e. support limb) in the recovery response. For example, the push-off generated by this limb provides additional time and clearance (~ 6% additional body elevation) for positioning the perturbed limb and facilitates recovery by attenuating the angular momentum of the body (Pijnappels et al. 2004). Furthermore, muscle onset latencies of the support limb range from 60 – 80 ms (Pijnappels et al. 2005b,c), which results in large ankle plantar flexion, knee flexion, and hip extension moments to cause push-off and control the angular momentum described above (Pijnappels et al. 2005c).

In summary, the recovery responses following perturbations to locomotion are geared towards maintaining dynamic stability. Specifically, studies have shown that (1) the recovery response is elicited extremely fast, between 60 and 200 ms after the perturbation, and organized in a highly functional way; (2) the recovery response following the first perturbation exposure is clearly different than subsequent ones; (3) the whole body is active in the recovery response such that there is intra- and inter-limb coordination of both the legs and arms; and (4) knowledge of the upcoming perturbation drastically alters the recovery response.

Although the studies mentioned above provide useful information, they are restricted in that (1) the vast majority of studies utilize a reactive paradigm where individuals are unaware of the onset of the impending perturbation and (2) only a single perturbation is used and thus, may not adequately represent a realistic environment where many different obstacles and ground terrain are present. Therefore, there is a need to move to studies using multiple perturbations, which are visible rather than hidden (or unexpected in nature). Only then may we begin to appreciate the complexity of the CNS for organizing complex recovery responses and adapting to different environmental conditions. In addition, this would allow us to better understand why individuals, particularly older adults, fall when encountering challenging ground terrain.

#### 1.3.2.2 Effects of aging on stability during locomotion

The process of aging can lead to poor vision, muscle weakness, decreased sensation including two-point discrimination and joint position sense, slower cognitive processing, neuronal loss in the motor cortex, vestibular hair cell loss, increased postural sway, impaired mobility and balance, and increased risk of falls (Daley and Spinks 2000; Mooreland et al. 2004; Prince et al. 1997; Tinetti et al. 1988; Watson 2001). These sensorimotor impairments have the potential to decrease stability while walking and may contribute to the large number of falls in this population. In fact, a delay in peak dorsiflexion power of the ankle and reduced range of motion can predict falling among older adults (Kemoun et al. 2002). The consequences of aging presumably would make responding to challenging walking environments even more difficult as a large proportion of falls occur during walking (Berg et al. 1997; Blake et al. 1988; Norton et al. 1997). Older adults show greater difficulty walking under conditions with low light and cognitive demand as demonstrated by increased time on a newly designed walking version of the neuropsychological Trail Making Test (Alexander et al. 2005). Surprisingly, only a few studies have investigated stability in older adults during walking in complex and challenging environments. These include studies on the recovery responses to tripping (Pijnappels et al. 2005a,b; Pavol et al. 2001; Schillings et al. 2005) and slipping (Chambers and Cham, 2006; Tang and Woollacott 1998, 1999), obstacle avoidance (Weerdesteyn et al. 2005), and walking on irregular surfaces (Menz et al. 2003a,c; Thies et al. 2005a). Yang and Ashton-Miller (2006) have also investigated stepping onto a raised compliant surface and shown that older adults require more time to regain balance and demonstrate less lateral COM movement toward the lead foot.

Older adults who fall in response to an unexpected trip during locomotion show faster walking velocity prior to the perturbation and increased trunk flexion following the trip (Pavol et al. 2001). In general, lower extremity muscle activation is delayed and the amplitude, particularly for later responses (ranging from 80 – 160 ms), is attenuated in older adults compared to young adults (Schillings et al. 2005). In fact, response time is critical for older adults to recover from a trip (van den Bogert et al. 2002). Furthermore, the ability of the support limb to contribute to recovery following a trip during locomotion is reduced in older adults as evident from a decreased rate of change of moment generation leading to a reduced ability to control the angular momentum during push-off (Pijnappels et al. 2005a) as well as delayed soleus muscle onset latency, attenuation of the magnitude of support limb muscle activity, and a slower rate of development of muscle activity (Pijnappels et al. 2005b). In response to an unexpected slip during walking, older adults' postural reflexes exhibit longer onset latencies, reduced magnitude, and longer burst durations compared to young adults (Tang and Woollacott 1998, 1999). In addition, older adults have more difficulty perceiving floor slipperiness (Lockhart et al. 2002) and demonstrate a greater number of falls, increased heel contact velocity, and longer slip distance than young adults

(Lockhart et al. 2003). Thus, across a range of unexpected unstable terrain, older adults have delayed and weaker responses than healthy young adults.

On irregular terrain (similar to that used in the experiments in this thesis), step width variability is increased in older women (Thies et al. 2005a). Compared to young adults, gait speed is reduced, step length decreased, and step timing variability is increased (i.e. a cautious walking strategy is adopted) in older adults (Menz et al. 2003a). While head and pelvis accelerations are smaller in the older adults, the smoothness of the acceleration profiles are not different compared to young adults. Moreover, older adults at risk of falling adopt a cautious walking strategy (e.g. slower velocity and reduced step length) and show impaired head and pelvis acceleration patterns (i.e. decreased harmonic ratios) in the vertical and anterior-posterior directions compared to older adults with less risk for falling when walking on irregular surfaces (Menz et al. 2003c). Older adults with peripheral neuropathy also show deficits when walking on irregular terrain under low light conditions including greater step width, step width and length variability, and decreased gait speed (Richardson et al. 2004, 2005; Thies et al. 2005b).

Over the last several years, Means and colleagues (Means 1996; Means et al. 1996a,b; Means and O'Sullivan 2000; Means et al. 1998a,b) have developed an obstacle course (referred to as the functional obstacle course) with different types of terrain (i.e. sand, carpet, artificial turf, and pine bark chips) and environmental challenges (i.e. stairs, ramps, and obstacles). The functional course was designed from a clinical perspective to be used to assess balance and mobility in older adults. While they have not explored the neural mechanisms or factors influencing stability, they have shown that an exercise program focusing on balance, coordination, and strength training leads to significantly better performance on the obstacle course and reduced prospective falls in the community (Means et al. 2005). In addition, Li et al. (2005) have shown benefits in physical function following cobblestone mat walking in older adults and Weerdesteyn et al. (2006) found a reduced incidence of falling in older adults following an exercise intervention utilizing an obstacle course featuring uneven terrain and different ground surfaces. Thus, exercise training on different types of ground terrain demonstrates improvements in balance and mobility and a reduced risk of falling. However, we still know very little about how young and older adults actually negotiate different and challenging terrain.

## 1.4 Research questions

Several research questions and their hypotheses are posed in order to address the purpose of this thesis. Experiments were conducted using healthy young adults and healthy older adults to answer these questions. The following are the research questions, which will guide this thesis, along with a brief statement of how they contribute to the overall thesis and/or our research knowledge base. Important for several of these studies is the concept of dynamic stability (or simply, stability). As previously mentioned, dynamic stability entails controlling the body's COM within a changing base of support (Patla 2003). In this thesis, stability was measured by examining trunk and/or head movement, trunk pitch and roll, and the relationship between the trunk COM and an ankle position marker on the lead foot (an estimate of the edge of the base of support). The trunk and head segments where chosen as the bulk of the body's mass is located in these regions (Winter 1991). Research questions 1, 2, 3, 4 and 5 are addressed in Chapters 2, 3, 4, 5, and 6, respectively.

### 1.4.1 Research question #1

*How is stability influenced by multiple steps on the same unstable surface and between different types of surfaces? Does this depend on age? How is stability affected when the unstable surfaces are along an edge of an elevated walkway?*

This study attempts to bridge the gap between previous research investigating single perturbations on an unstable surface and the subsequent studies examining how individuals negotiate varying ground terrain in the travel path. The previous studies have predominantly focused on reactive control strategies in that the perturbation was unexpected in nature. In contrast, in the present study the surfaces are clearly visible throughout (which is similar to subsequent studies in this thesis). Thus, individuals can proactively adjust to the terrain. As the walkway containing the different ground terrain is slightly elevated (~0.1 m), another objective of this particular study was to determine whether stability is influenced by surfaces placed on the edge compared to the middle of the walkway. Finally, this study examines the different stability challenges posed by three of the surfaces that will be used in the subsequent studies.

Hypotheses: Older adults will demonstrate greater challenges to stability as evident from increased trunk/head COM movement and increased trunk angle oscillations compared to young adults. In addition, stability will be compromised to a greater extent when walking along the surfaces next to the edge of the walkway. Of the three different types of surfaces used in this study (i.e. irregular, compliant, and uneven), stability will be most affected when walking on the compliant terrain regardless of age.

### 1.4.2 Research question #2

*Where and when do people look while negotiating varying ground terrain?*

The visual system is unique in that it is the only sensory system that can provide information about features of the environment important for successful locomotion at a distance. Details of the environment can be obtained through a series of fixations directed to salient objects and/or surfaces. Unfortunately, no studies have examined how visual information is acquired in situations where the ground terrain is challenging and vision presumably guides foot placement. Furthermore, it is important to determine what specific types of surfaces and/or landmarks are fixated as this will give clues as to what visual information is important for performing this task.

Hypotheses: Visual fixations will be directed to some surfaces more than others. For example, solid surfaces will be fixated frequently so as to target stepping on them due to their surface characteristics (i.e. stable). Furthermore, fixations will be directed equally to surfaces that will eventually be stepped on and those that will be avoided (due to the perceived threat of the surface). In addition, fixations will be directed only a few steps ahead rather than individuals using a scanning strategy and fixating the entire layout.

### 1.4.3 Research question #3

*How does aging influence where and when you look while negotiating varying ground terrain?*

Many older adults demonstrate reduced visual function (e.g. decreased contrast sensitivity) and suffer from many visual disorders such as cataracts. Thus, in tasks which rely heavily on vision, older adults may show deficits. In the context of walking, falls may result if important visual information is not acquired. However, very few studies have investigated fixation patterns in older adults.

Hypotheses: Fixations of older adults will resemble those of young adults (see hypotheses of research question #2). However, older adults will fixate further ahead (i.e. last few rows of unstable surfaces) early in the travel path in order to provide more time to acquire terrain layout characteristics to safely plan their route. In addition, fixation durations will be longer in older adults compared to young adults as the cognitive abilities of older adults are known to be slower.

### 1.4.4 Research question #4

*How does aging influence stability across varying ground terrain?*

Healthy older adults have a higher rate of falling than younger adults. This risk is increased among frail older adults. Most studies on stability during locomotion in an older adult population have focused on single perturbations. However, in reality the terrain we encounter is composed of many different surface characteristics which each pose a certain challenge. Thus, we will investigate the effect of aging in this context in an attempt to better understand falling in this population.

Hypotheses: Older adults will demonstrate slower gait speed, increased trunk COM acceleration, increased step width, decreased step length, and fall more frequently than young adults while walking across the varying ground terrain.

### 1.4.5 Research question #5

*Is the lower peripheral visual field critical for negotiating varying ground terrain?*

Reaching and grasping performance is better in the lower visual field and the lower visual field seems to map onto the dorsal visual stream, which is critical for the visuomotor control of action (foot placement in our task) (Brown et al. 2005; Danckert and Goodale 2001). In addition, we know that limb trajectory over obstacles is monitored on-line via the lower visual field and as such, foot placement may be compromised when blocking vision from the lower visual field in our task as well. Results from the second study (research question #2) suggest that visual information about the terrain layout is sampled approximately two steps ahead while on the challenging terrain. However, it is not known whether visual exproprioceptive information regarding the lower limb and ground terrain immediately in front is critical for safe foot placement on the different surfaces.

Hypotheses: Blocking the lower visual field will cause individuals to pitch their head downward to a greater extent in order to sample visual information from the lower visual field and stability will be compromised for both young and older adults as reflected by changes in head movement, trunk motion, and foot placement (i.e. step length and width).

# CHAPTER 2 - Insights into the age-related differences in walking across challenging terrain

## 2.1 Abstract

While we frequently encounter different types of ground terrain as we ambulate in our environment, little research has been done to understand how we negotiate this terrain. This is despite the increased fall risk among older adults and the known decline in sensorimotor function associated with aging. Therefore, the purpose of this study was twofold. First, to determine the effects of aging and surface type on stability while walking across different types of ground terrain. And second, to determine whether stability is altered by walking on different types of ground terrain, which are positioned along the edge of an elevated walkway. Ten healthy young and ten healthy older adults walked across four different types of surfaces (solid, compliant, irregular, or uneven) positioned either in the middle or along the edge of a walkway. Position markers on the ankles, trunk, and head recorded kinematics and anterior-posterior (AP) and medial-lateral (ML) trunk/head centre of mass (COM) velocity and trunk pitch and roll root-mean-square (RMS) deviation were determined along with step parameters. While young and older adults were more unstable when traversing the different ground terrain compared to solid ground, stability was most affected in the sagittal plane while walking on the compliant terrain and in the frontal plane while walking on the uneven terrain. The young adults were more unstable in the AP direction when walking on the different ground terrain as reflected by an increased AP trunk/head COM velocity RMS. This was most likely due to the cautious walking strategy (slower gait speed and shorter step length) adopted by the older adults since increased gait speed is associated with greater trunk movement. However, despite this slower gait speed trunk stability was not different between age groups in the ML direction. There was relatively little influence on stability when the challenging ground terrain was positioned along an elevated edge. The results suggest that frontal plane stability may be compromised with increasing age and further research is warranted.

## 2.2 Introduction

The aging nervous system must deal with sensorimotor deficits when negotiating varying ground terrain in the environment. As such, balance may be compromised when walking on unstable surfaces. However, little is known about how the nervous system controls balance in these situations and how stability is affected in both young and older adults. This is somewhat disconcerting considering the high incidence of falls among older adults (Berg et al. 1997; Blake et al. 1988; Norton et al. 1997; Tinetti et al. 1988) and the frequency with which people experience ground irregularities when walking. Understanding the changes in stability with age while walking on challenging ground terrain and hence identifying potential fall mechanisms is essential to improve quality of life in these individuals and reduce the burden on the health care system in treating fall-related injuries.

Few studies have investigated stability when taking multiple steps on the same unstable surface (MacLellan and Patla 2006; Menz et al. 2003a,b,c). Rather, the majority of research has focused on single step perturbations while walking (Bhatt et al. 2006; Cham and Redfern 2001; Marigold and Patla 2002, 2005; Marigold et al. 2003; Oates et al. 2005). Further, these studies have primarily investigated reactive control strategies: the perturbations to balance were unexpected in nature. However, knowledge and experience of an upcoming hazardous surface elicits modifications to the gait pattern and recovery responses (Heiden et al. 2006; Marigold and Patla 2002). Thus, the present study was geared towards advancing our understanding of how stability is compromised when walking (i.e. multiple steps) on different types of unstable ground terrain when the surfaces were readily visible.

On compliant terrain, MacLellan and Patla (2006) have demonstrated that young adults increase toe trajectory during swing phase to avoid tripping, increase step length and width, and show greater forward trunk pitch compared to walking on solid ground. On irregular terrain, Menz et al. (2003b) have shown young adults walk more slowly, exhibit longer step lengths and have increased pelvis acceleration compared to level walking. Healthy older adults demonstrate increased step width variability, reduced gait speed and decreased step length compared to young adults when walking across irregular terrain

(Menz et al. 2003a; Thies et al. 2005a). In addition, the smoothness of head and pelvis acceleration patterns are decreased in older adults at risk for falls (Menz et al. 2003c). Furthermore, step width and step width and length variability are increased in older adults with peripheral neuropathy when walking on irregular terrain under low light conditions (Richardson et al. 2004, 2005; Thies et al. 2005b).

When challenging terrain is close to an edge, such as a curb along a sidewalk, the threat of losing balance may be heightened. This is especially the case when a fall or step off the edge (or curb) results in putting oneself in danger, such as in front of a moving vehicle. Young individuals adopt a stiffening strategy when standing on the edge of an elevated platform characterized by a decrease in centre of pressure displacement, increase in mean power frequency, and decreased deviation of the anterior-posterior centre of mass displacement (Carpenter et al. 1999, 2001). Walking along an elevated narrow beam results in a decrease in gait speed and several other age-related changes to the gait pattern (Brown et al. 2002). For example, older adults showed less joint range of motion and joint angular velocities compared to young adults (Brown et al. 2002). However, research examining walking along an elevated edge is still limited, particularly when the terrain is capable of destabilizing balance.

The goal of this study was twofold. First, to determine the effects of aging on stability while walking across different types of ground terrain. We also asked whether a particular surface was more challenging than the others. Second, to determine whether stability is altered by walking on different types of ground terrain, which are positioned along the edge of an elevated walkway (similar to a street curb).

## 2.3 Methods

### 2.3.1 Participants

Ten healthy young adults (5 female, 5 male; mean ± SD age = 26.1 ± 5.2 yrs.) and ten healthy older adults (5 female, 5 male; mean ± SD age = 74.1 ± 7.2 yrs.) volunteered for this study. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behaviour in this study. Participants wore corrective lenses if necessary. Balance confidence, functional mobility, and visuomotor processing ability were assessed using the Activities-specific balance confidence (ABC) scale (Powell and Myers 1995), timed up and go test (Podsiadlo and Richardson 1991), and the Trail Making Test (part A and B) (Tombaugh 2004), respectively, to provide an overall picture of the young and older adults (see Table 2.1).

The study was approved by the Office of Research Ethics at the University of Waterloo and informed written consent was received from all participants.

**Table 2.1:** Participant characteristics.

| Characteristics* | Young Adults (N = 10) | Older Adults (N = 10) |
|---|---|---|
| **Age, years** | 26.1 ± 5.2 (20 - 37) | 74.1 ± 7.2 (61 - 82) |
| **Gender, Male/Female** | 5/5 | 5/5 |
| **Timed Up and Go, seconds** | NA | 9.7 ± 1.9 (8.0 - 13.6) |
| **ABC scale, %** | 96.4 ± 3.5 (88.1 - 100) | 93.4 ± 7.1 (81.9 - 100) |
| **Trail Making Test A, seconds** | 16.3 ± 2.5 (12.9 - 19.3) | 31.0 ± 10.7 (20.8 - 51.4) |
| **Trail Making Test B, seconds** | 35.6 ± 14.6 (24.4 - 75.1) | 65.6 ± 28.1 (44.0 - 138.4) |

*Date are mean ± SD (range)

NA = not available

### 2.3.2 Protocol

Participants were required to walk at a self-selected pace along a painted (medium shade of grey) wooden walkway (~8.5 m long, ~1.5 m wide and elevated ~0.1 m) where the middle portion consisted of solid uniform ground (i.e. control condition) or one of three different types of surfaces. The three different surfaces were either irregular, compliant, or uneven (tilt) ground terrain. The irregular surfaces had irregularly spaced custom-made dark grey rock-climbing holds mounted on the top, the height of which ranged from 1 to 3 cm and the spacing between holds ranged from 2 to 5 cm. The compliant surfaces were composed of medium-density foam (stiffness ~13 kN/m; maximum compression of ~0.08 m) and covered with a thin green fabric (to simulate wet, soggy, grass). The tilt (or uneven) surfaces were constructed such that they had a 10º downward tilt (either to the left or right in the frontal plane). Three blocks (~0.5m x 0.5m x 0.1m) of one particular surface type were arranged one after the other in the middle (lengthwise) portion of the walkway (irregular, compliant, or tilt conditions). The tilt surfaces were positioned such that the first surface tilted to the right, the second tilted to the left, and third tilted to the right again. The three surfaces of the same type were either positioned in the middle (Middle condition) or along the edge (Edge condition) of the walkway (see Fig. 2.1). Thus, there were four surface conditions (control, irregular, compliant, and tilt) and two configuration conditions (Middle and Edge). The order of configuration conditions was randomized among the participants; however, all trials for each configuration were performed before switching to the other configuration. Blocks of three trials of each surface type were randomized within each configuration.

Three Optotrak cameras were used to collect kinematic data (sampling frequency of 60 Hz) and a video camera recorded the walking trials from the left side of the participant's body for qualitative observations. Position markers (infrared emitting diodes) were placed bilaterally on the ankles, iliac crests, and sternal end of the clavicles, as well as on the xyphoid process, chin, and head. For the head, a plastic band was used that contained a cluster of five markers centered on the forehead and a marker off to the side (closer to the left ear). A custom-written program in MATLAB low-pass filtered the position data for all markers at 6 Hz ($2^{nd}$ order, dual-pass, Butterworth algorithm) and processed all data.

### 2.3.4 Data analysis

Foot contacts on the multi-surface terrain (or control walking trials equivalent) were determined based on the displacement profiles of the ankle markers using a computer algorithm combined with visual inspection. The mean step length and width (based on the displacement data of the ankle markers) were calculated. Gait speed was based on the displacement data of the xyphoid position marker.

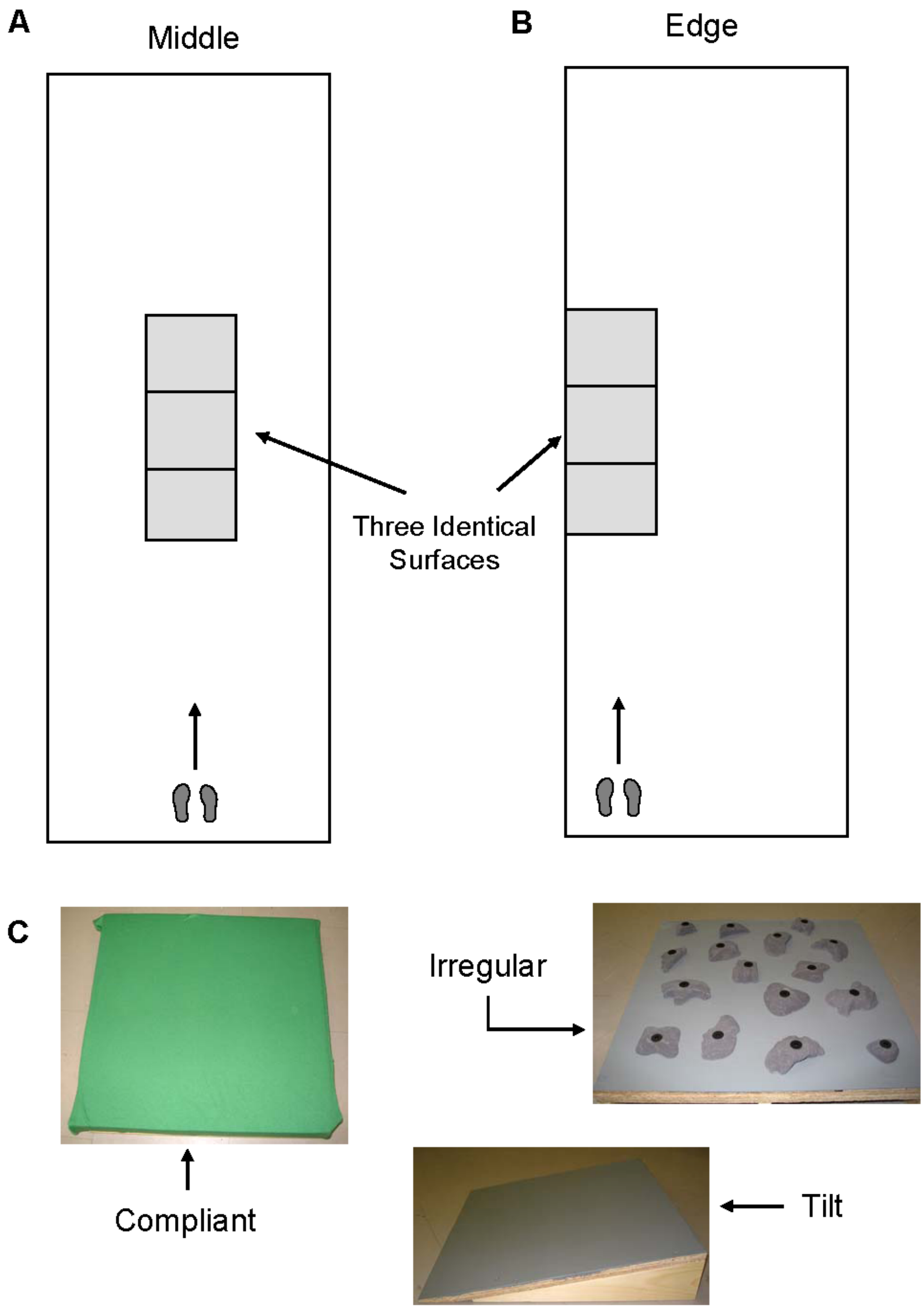



**Figure 2.1:** Experimental set-up. (A) Set-up for the Middle condition, where surfaces were placed along the middle of the walkway. (B) Set-up for the Edge condition, where surfaces were placed along the edge of the walkway. (C) The three surface types (i.e. compliant, irregular, and tilt) used in addition to a solid surface.

Trunk/head centre of mass (COM) was calculated from the iliac crest, xyphoid, clavicle, and head position markers using anthropometric data and segment definitions from Winter (2005). The anterior-posterior (AP) and medial-lateral (ML) trunk/head COM velocities were determined by differentiating the AP and ML COM displacement data. Trunk pitch was calculated as the angle between a vertical line (orthogonal to the plane of progression) and a line joining the bisection of the iliac crest position markers and bisection of the clavicle markers in the sagittal plane (Marigold and Patla 2005). Trunk roll was calculated as the angle between a vertical line (orthogonal to the plane of progression) and a line joining the bisection of the iliac crest markers and bisection of the clavicle markers in the frontal plane (Marigold and Patla 2005). The trunk/head AP and ML COM velocities and trunk angles were determined from foot contact on the first surface until foot lift-off from the last surface (or control condition equivalent). Subsequently, the root-mean-square (RMS) deviation (i.e. standard deviation) was calculated for each measure during this time interval and reflected stability while walking on the different ground terrain: larger RMS values indicating less stability.

AP and ML stability margins (SM) based on the location of the trunk/head COM and ankle position markers (an estimate of the edge of the base of support) were also determined at each foot contact on the different ground terrain (or control condition equivalent) and then averaged. The AP-SM was calculated by subtracting the lead foot AP ankle marker position from the AP trunk/head COM position such that negative values indicated the trunk/head COM behind the lead foot with values approaching zero representing the COM coming closer to the ankle marker of the lead foot. The ML-SM was calculated by subtracting the ML ankle marker position of the lead foot from the ML trunk/head COM position and corrected based on which foot was leading so that positive values indicated the ML trunk/head COM medial to the lead foot.

### 2.3.5 Statistical analysis

The data were rank transformed, where appropriate, if the data was not normally distributed (as determined by examination of normality plots in conjunction with the Kolmogorov-

Smirnov test). An alpha level of 0.05 was chosen for significance for all statistical analyses.

In order to determine how stability is influenced by the different surfaces and between age groups we performed a two-way ANOVA on each measure with surface type (control, compliant, irregular, and tilt) as the within-subject factor and age (young and older) as the between subject factor (edge trials not included in the analysis). To determine the effect of the surfaces along the edge we performed a three-way ANOVA on each measure with surface type (compliant, irregular, and tilt surfaces only) and configuration (middle and edge) as within-subject factors and age (young and older) as a between subject factor. In this latter analysis, we were only interested in the Configuration main effects and Age X Configuration and Age X Configuration X Surface interactions.

## 2.4 Results

### 2.4.1 Influence of surface type on stability: surfaces along the middle of the walkway

Gait speed varied according to age group (Fig. 2.2). Gait speed demonstrated an Age main effect ($F_{1,18} = 20.73$, $P = 0.0002$) and Age X Surface interaction ($F_{3,54} = 4.41$, $P = 0.008$). Post hoc analyses demonstrated that young adults were faster than the older adults for the control, compliant, irregular, and tilt surfaces.

Accompanying the change in gait speed were Surface main effects for step length ($F_{3,54} = 4.81$, $P = 0.005$) and step width ($F_{3,54} = 5.38$, $P = 0.003$) and an Age main effect of step length ($F_{1,18} = 21.66$, $P = 0.0002$) (see Fig. 2.2). Post hoc analyses showed that step length was dramatically reduced among the older adults compared to the young adults and was shorter when stepping on the tilt surfaces compared to the other surfaces. Furthermore, step width was decreased in the compliant surface condition compared to the other surfaces.

The most noticeable change in stability when negotiating the hazardous terrain was in the AP direction. Trunk pitch RMS and trunk/head AP COM velocity RMS were increased when walking on the different terrain (Fig. 2.3a,b). This was particularly evident when

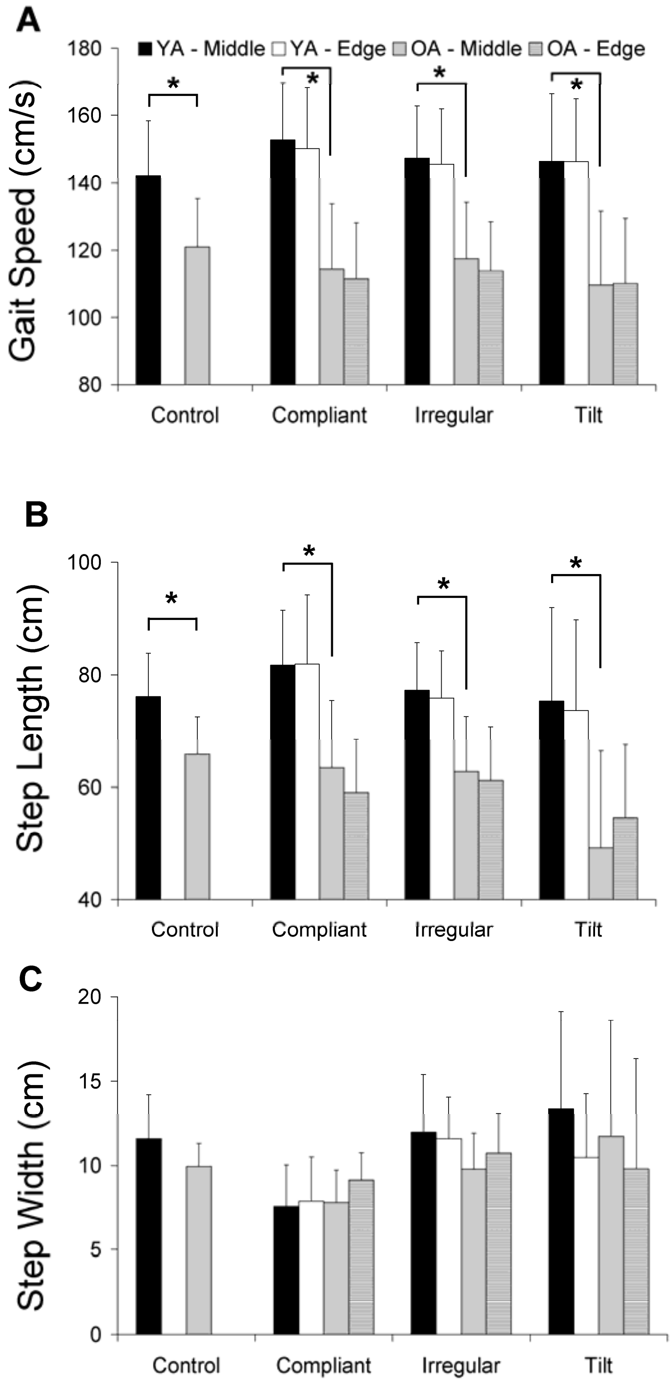



**Figure 2.2:** Gait speed (A), step length (B), and step width (C) for each surface type among the young adults (YA) and older adults (OA) for the middle and edge configurations. Error bars represent standard deviation. Asterisks indicate the effects of age (P < 0.05).

traversing the compliant terrain. Trunk/head AP COM velocity RMS and trunk pitch RMS demonstrated a main effect of Surface type ($F_{3,54} = 22.21$, $P < 0.0001$ and $F_{3,54} = 50.71$, $P < 0.0001$, respectively) with the smallest RMS values for the control surface and highest for the compliant surfaces. There was also an Age X Surface interaction ($F_{3,54} = 5.40$, $P = 0.003$) for trunk/head AP COM velocity RMS where post hoc analyses demonstrated that the young adults had larger RMS values for the compliant and tilt surfaces but there was no difference in the control or irregular conditions.

In the ML direction, there was a main effect of Surface type for both the trunk/head ML COM velocity RMS ($F_{3,54} = 5.52$, $P = 0.002$) and trunk roll RMS ($F_{3,54} = 9.98$, $P < 0.0001$) measures (see Fig. 2.3c,d). However, the surfaces influenced these measures differently. Specifically, trunk/head ML COM velocity RMS was larger when walking on the tilt surfaces than any other surface. In contrast, trunk roll RMS was largest when walking on any of the hazardous terrain (compliant, irregular, and tilt surfaces) compared to the control surface condition.

Fig. 2.4 illustrates the changes in stability margins according to which surface individuals were walking across. The AP-SM showed an effect of Age (main effect: $F_{1,18} = 15.01$, $P = 0.001$) and Surface type (main effect: $F_{3,54} = 9.25$, $P < 0.0001$). As seen in the figure, older adults had a smaller AP-SM suggesting that the trunk/head COM was closer to the estimated base of support of the lead limb (i.e. estimated from the ankle marker). Furthermore, post hoc analysis indicated that the AP-SM was smaller when walking across the compliant terrain compared to the other surfaces suggesting the trunk/head COM was closer to the estimated base of support when walking on this surface. The ML-SM also showed a Surface main effect ($F_{3,54} = 8.90$, $P < 0.0001$), which post hoc analyses indicated the stability margin in this direction was smallest when traversing the compliant surface followed by the control and irregular surfaces and then the tilt surfaces. Thus, the trunk/head COM was closest to the estimated base of support in the ML direction when traversing the compliant terrain and farthest away when traversing the tilt terrain.

Despite being less stable when walking on the different ground terrain young and older adults did not fall on any trials.

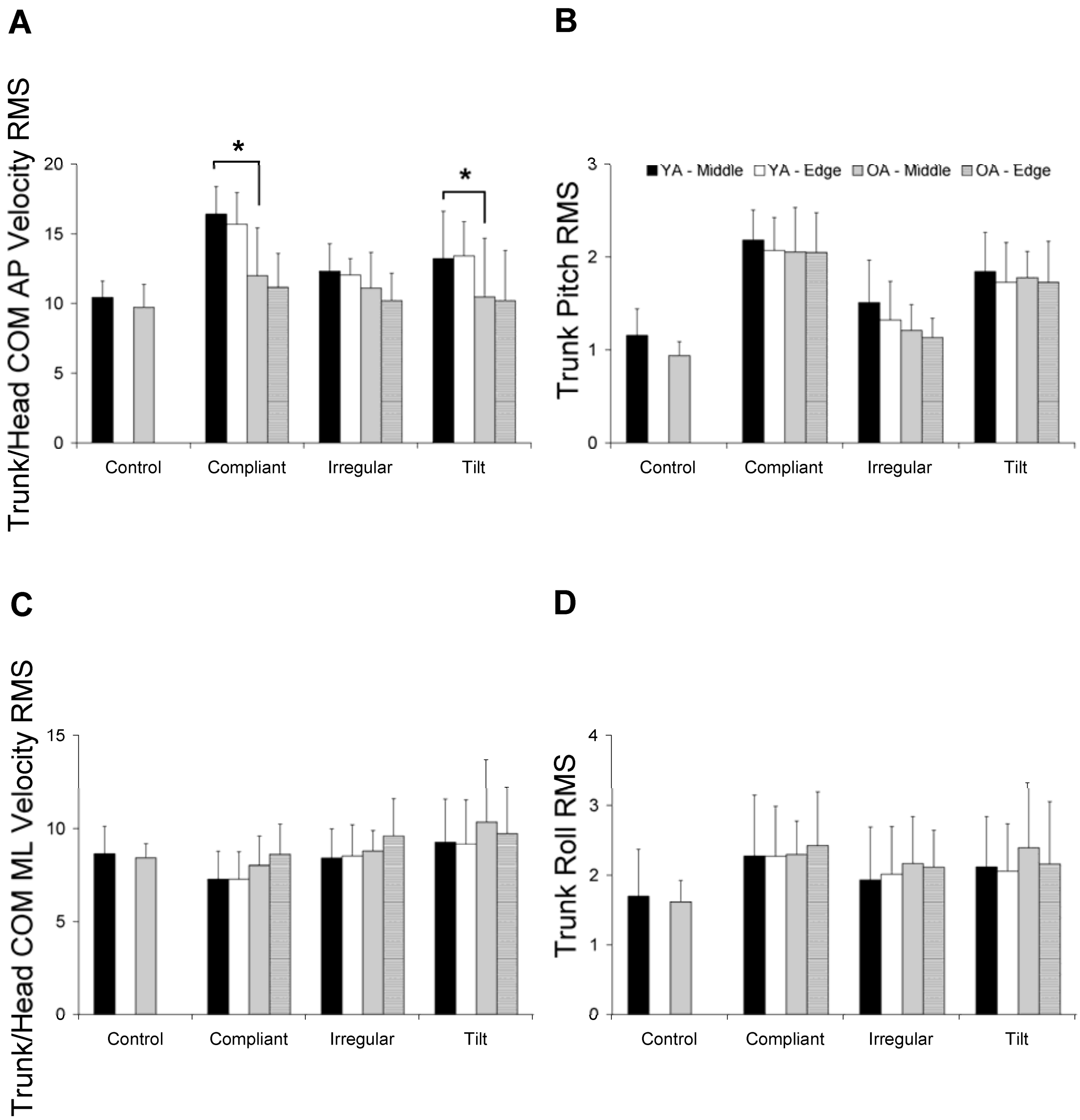



**Figure 2.3:** Trunk stability measures for the young (YA) and older (OA) adults for each surface type and the middle and edge configurations. Illustrated is the trunk/head COM acceleration RMS measure for the (A) AP direction and (C) ML direction. Also shown are the (B) trunk pitch and (D) trunk roll angle RMS measures. Error bars represent standard deviation. Asterisks indicate the effects of age ($P < 0.05$).

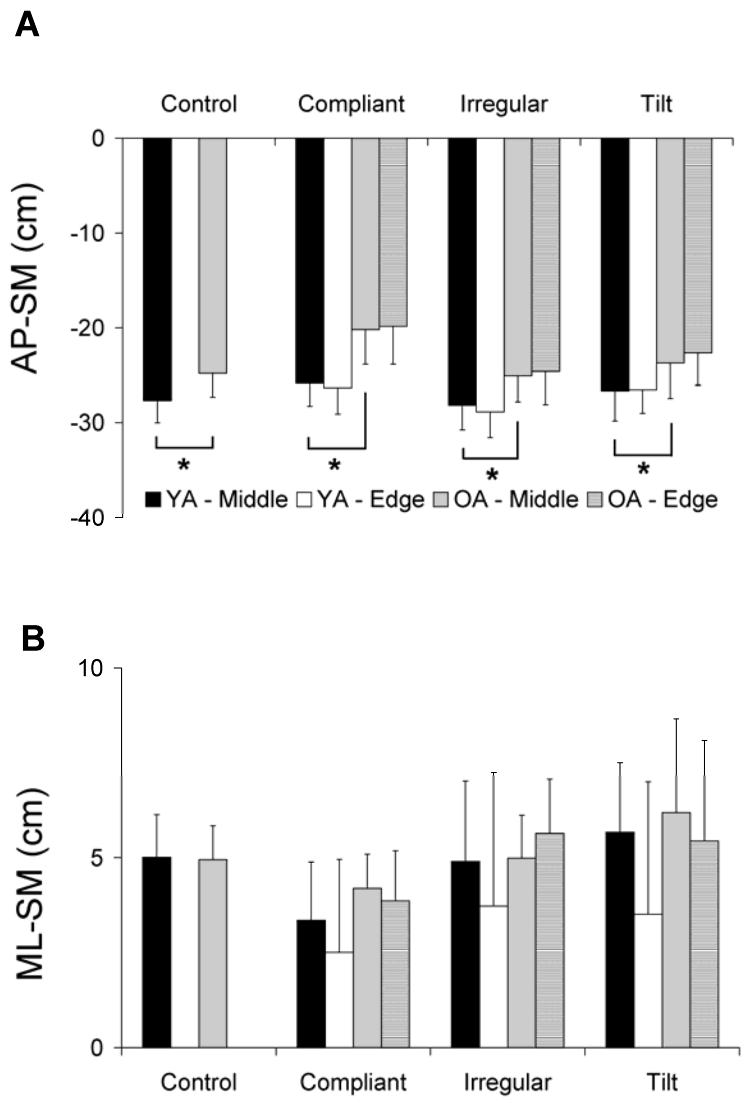



**Figure 2.4:** (A) AP and (B) ML stability margins for the young (YA) and older (OA) adults for each surface (control, irregular, compliant, and tilt) and configuration (middle and edge) type. Values closer to zero indicate the trunk/head COM is closer to the ankle marker of the lead foot. Error bars represent standard deviation. Asterisks indicate the effects of age ($P < 0.05$).

### 2.4.2 Influence of surfaces positioned on edge of elevated walkway on stability

There was relatively little effect of walking on the different surfaces while they were positioned along the edge of a ~0.1m elevated walkway as illustrated in Figs. 2.2-2.4. There were no Configuration main effects or Age X Configuration and Age X

Configuration X Surface interactions ($P > 0.05$) for all measures with the exception of trunk pitch RMS (see Fig. 2.3). Trunk pitch RMS was decreased in the Edge condition compared to the Middle condition regardless of Age and Surface type (Configuration main effect: $F_{1,18} = 5.11$, $P = 0.036$).

## 2.5 Discussion

### 2.5.1 Effect of surface type and age on stability during locomotion on different ground terrain

The ability to safely negotiate hazardous and continually changing ground terrain as we walk in the environment is paramount to our ability to survive. Despite this, little research has been done to examine how individuals accomplish this task. Given the risk of falling among adults over the age of 65, we questioned how aging would influence stability while walking across different types of ground terrain. Young adults demonstrated greater instability in the AP direction compared to older adults when negotiating the different ground terrain. Older adults walked more cautiously as reflected by a slower gait speed and shorter step length compared to the young adults. This may partially explain the lower RMS values of the trunk/head AP COM velocity measure. Gait speed does influence trunk movement: faster gait speed is related to increased trunk movement (Menz et al. 2003a). Similarly, Menz et al. (2003a) have shown that stability is generally more compromised in young adults compared to older adults as reflected by increased head and pelvis acceleration RMS when walking on irregular terrain. However, older adults have smaller AP-SM values indicating that their trunk/head COM was closer to the lead limb estimated base of support at each foot contact in the AP direction, which is suggestive of greater difficulty maintaining balance or may reflect a different strategy than the young adults. Indeed, the shorter step length as part of the cautious gait strategy could cause this reduction in stability margin.

Interestingly, we found no age differences in ML stability in terms of trunk roll and trunk/head ML COM velocity. This is despite the fact that young adults walked more quickly. Helbostad and Moe-Nilssen (2003) have shown that faster gait speed among older adults is associated with larger ML trunk acceleration RMS. Thus, it is possible that older adults are more unstable in the frontal plane than young adults and reducing gait speed allows stability to match that of a younger adult. One reason for the slower gait speed observed among the older adults may be from impaired visuomotor processing ability. The older adults' demonstrated longer durations to complete the Trail Making Test A and B compared to young adults (see Table 2.1). Gait speed is inversely related to the time to complete these tests ($r = -0.63$, $P = 0.0003$ and $r = -0.58$, $P = 0.007$ for parts A and B, respectively) such that those individuals who walk slower take longer to complete both parts of the Trail Making Test.

An interesting question to ask is what surface was most challenging? Compliant terrain is prevalent in situations where one is walking on loose dirt, sand, soggy grass, and snow. Ankle proprioceptive information can be severely altered when stepping on this type of terrain. This may increase fall risk as the altered ankle proprioceptive information may create difficulties in producing sufficient ankle torque to recover from the perturbation to balance. Indeed, the inability to adequately and quickly generate ankle torque is related to a reduced ability to recover balance from a forward directed fall (Mackey and Robinovitch 2006). Further, reduced lower limb proprioception is related to fall risk and lateral instability (Lord et al. 1999). In addition, load related information may be compromised when stepping on this terrain as weight bearing on the expected level solid ground is delayed as a result of the compression of the surface. Irregular terrain, present on many sidewalks and streets, provides different sensory cues to the plantar surface of the foot, which would be sensed by cutaneous mechanoreceptors. Older adults exhibit deficits in cutaneous sensation from this area (Perry 2006), which may increase the likelihood of falling. Finally, uneven (or tilting) surfaces are also highly prevalent on sidewalks and streets. Stepping on a laterally directed slope as present in the current study would induce increased ankle inversion or eversion depending on how the person steps. This could increase the risk of a lateral fall, which is related to an increase in hip fracture risk (Nankaku et al. 2005; Robinovitch et al. 1991). When individuals step on an unexpected ankle inverting platform Nieuwenhuijzen and Duysens (2005) have shown whole-body responses, particularly a lateral shift of the knee to decrease the effect of ankle inversion.

Clearly illustrated in this study is the fact that the irregular terrain posed the least difficulty in terms of maintaining stability. What is also evident is that the compliant terrain posed the most difficulty in terms of maintaining stability in the AP direction (see Fig. 2.3). Trunk/head AP COM velocity RMS and trunk pitch RMS were dramatically increased when traversing the compliant terrain compared to the other surfaces. We have seen large forward trunk pitch when young adults walk on visibly compliant terrain (MacLellan and Patla 2006) and when stepping on this type of surface is unexpected (Marigold and Patla 2005). Although less clear, it can be argued that the tilt terrain posed the greatest challenge in the ML direction. There are two reasons for this argument. First, trunk/head ML COM velocity RMS was largest when walking on these surfaces. Second, the ML-SM was largest when walking on the tilt surfaces. This latter finding could be a result of a cautious strategy in that individuals attempt to maximize safety by ensuring the trunk/head COM does not venture to close to the lateral edge of the base of support of the lead limb.

### 2.5.2 Effect of unstable ground terrain along the edge of an elevated walking path

A second question we asked was whether walking on hazardous terrain that is close to the edge of an elevated surface influenced stability. There were essentially no differences in terms of stability when walking on the different ground terrain when it was positioned along the edge of an elevated walkway or when it was placed in the middle. This is in contrast to a previous study that showed both young and older adults altered their gait pattern in similar situations (Brown et al. 2002). It is possible that the walkway height in our study was not deemed threatening. Consequently, a limitation of this study was not collecting information regarding perceived threat either through questionnaires or galvanic skin conductance. However, when asked whether participants were more anxious when walking on the different surfaces on the edge of the walkway neither the young or older adults seemed to notice any differences and indicated that it was not overly threatening. This may have been due in part to the use of a safety harness when walking.

While there were relatively no differences in the kinematic measures when surfaces were along the edge, changes in muscle activity may have been present. Indeed, Llewellyn et al. (1990) have reported lower H-reflex gain and reduced muscle activity when individuals walk on a narrow, elevated, beam compared to normal treadmill walking. We are currently examining whether changes in muscle activity occur in our task.

In conclusion, older adults show less AP trunk instability than young adults when walking on different types of ground terrain and ML trunk stability is not affected by age. The cautious gait strategy seen among the older adults may partially explain these results. Regardless of age, stability was compromised when negotiating the different terrain compared to walking on solid level ground. AP stability was most affected when traversing the compliant terrain and ML stability was most affected by the tilt (or uneven) terrain suggesting that if possible, surfaces with these types of characteristics should be avoided, particularly for individuals at risk of falling. Finally, challenging surfaces placed along an elevated edge do not alter stability. However, further work is required before any firm conclusions can be drawn.

## 2.6 Bridging summary

This experiment provides two important findings which facilitate our understanding of the remaining studies. First, of the surfaces tested the compliant terrain posed the greatest challenge to AP stability and the tilt surface posed the greatest challenge to ML stability. Thus, we might expect to see individuals choose to step on the irregular and solid terrain more than the compliant and tilt terrain when experiencing the multi-surface terrain in subsequent experiments. Second, having the unstable surfaces along the edge of a slightly elevated walking platform did not influence the kinematic measures. This is important since many different surfaces will be along the edge of the elevated platform for the multi-surface configurations utilized in the following experiments.

This experiment serves to bridge the gap between previous research on single perturbations (from a single unstable surface in the travel path) and more complex environments where there are many different types of unstable ground terrain in the travel path as in the subsequent experiments in this thesis.

**PERMISSION STATEMENT FROM PUBLISHER**

**From:** Jones, Jennifer (ELS-OXF) [mailto:J.Jones@elsevier.co.uk]
**Sent:** September 25, 2006 4:39 AM
**To:** Dan Marigold
**Subject:** RE: permission for using article in dissertation

ELSEVIER

Dear Dan Marigold

We hereby grant you permission to reproduce the material detailed below at no charge **in your thesis** subject to the following conditions:

1. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies.

2. Suitable acknowledgment to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

   "Reprinted from Publication title, Vol number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier".

3. Reproduction of this material is confined to the purpose for which permission is hereby given.

4. This permission is granted for non-exclusive world **English** rights only. For other languages please reapply separately for each one required. Permission excludes use in an electronic form. Should you have a specific electronic project in mind please reapply for permission.

5. This includes permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission.

Yours sincerely

Jennifer Jones
Rights Assistant

**PERMISSION STATEMENT FROM CO-AUTHOR**

Manuscript Details:

Marigold DS, Patla AE. Gaze fixation patterns for negotiating complex ground terrain. Neuroscience 2007; 144: 302-313.

As a co-author of the published manuscript detailed above, I Aftab Patla give permission to Daniel Marigold to use the manuscript in his PhD thesis. In addition, I Aftab Patla permit the microfilming of this thesis.


Aftab Patla

## CHAPTER 3 - Gaze fixation patterns for negotiating complex ground terrain



### 3.1 Abstract

We constantly encounter different ground terrain in our environment that we must safely traverse. The visual system is unique, as it is the only sensory system that can provide accurate and precise information about the environment at a distance through a series of fixations directed to salient objects and/or surfaces. However, how the nervous system utilizes visual information regarding complex ground terrain to guide safe foot placement is not known. We had individuals walk across a walkway with varying ground terrain while gaze fixations were monitored. Several findings emerged. First, gaze fixations were highly task-relevant in that they were predominantly made to areas eventually stepped on and their patterns tended to depend on the task instructions. Second, fixations were frequently directed to a transition region between different surfaces in addition to fixations directed to an actual surface. These results suggest that fixations are directed to regions that maximize the amount of information in which the nervous system can integrate in order to facilitate safe foot placement. And third, spatial information of the upcoming ground terrain was sampled sequentially in small sections and continuously updated as the individual traversed the challenging ground terrain. This is suggestive of on-line control and may be beneficial to ensure one is able to adapt to stability concerns, unexpected changes in terrain, or sudden changes in the path taken.

## 3.2 Introduction

The environment we ambulate throughout is complex and we continually encounter different ground terrain that must be safely negotiated to maintain balance. While the nervous system is capable of reacting to an unexpected loss of balance (Patla, 2003), often the best means of preventing a fall is to have information of the eliciting hazard ahead of time. For example, knowledge about the characteristics and presence of an upcoming slippery surface drastically alters the way in which a person steps on and reacts to the unstable terrain (Marigold and Patla, 2002). The visual system is unique in that it is the only sensory system that can provide information to the central nervous system (CNS) about features of the environment at a distance. Details of the environment can be obtained through a series of fixations directed to salient objects and/or surfaces as saccadic eye movements shift the image of interest onto the region of the retina with the highest visual acuity, the fovea.

Studies investigating eye movements across a range of tasks including driving (Land and Horwood, 1995; Land and Lee, 1994), tea-making (Land and Hayhoe, 2001; Land et al. 1999), sandwich-making (Hayhoe, 2000; Hayhoe et al. 2003; Land and Hayhoe, 2001), hand washing (Pelz and Canosa, 2001), object manipulation (Johansson et al. 2001), simple walking tasks (Hollands et al. 2002; Patla and Vickers, 1997, 2003), and crossing an intersection (Geruschat et al. 2003) have shown that fixations are directed to task-relevant areas and provide critical information for future actions. For example, Geruschat et al. (2003) found individuals fixate primarily on crossing elements (e.g. curbs and crosswalk lines) while approaching and crossing an intersection and fixate primarily on cars when waiting at the curb. Land and Lee (1994) have shown that drivers saccade to and fixate the tangent point (inside bend) of a curved road before and during the turn in order to predict the curvature of the road. More recently though, Wilkie and Wann (2003) found that active gaze during steering is essential and individuals fixate points on their future path rather than following the tangent point strategy. In particular, fixations were directed to points close to the intended path about 1-2.5 seconds ahead (Wilkie and Wann, 2003). This was similar to the look ahead fixations (i.e. sampling 1-2 seconds ahead) of Land and Lee (1994) during driving and of Patla and Vickers (2003) while walking on specific targets on the travel path.

The importance of visual information dramatically increases as the difficulty of the task intensifies (Patla, 1997; Patla et al. 1996). In situations where ground terrain is challenging, visual input provides spatial information regarding the layout of the environment and surface characteristics, in part, based on previous experience with similar surfaces. Further, the need for accurate foot placement is heightened to ensure stability is maintained. No studies have examined the role of vision, and in particular eye movements, in this context. Thus, the question remains as to how the nervous system utilizes visual information regarding complex ground terrain to guide safe foot placement and maintain stability during locomotion. Fajen and Warren (2003) have argued that visual information is used in an on-line manner to steer towards goals, avoid obstacles, and guide path selection on level uniform ground.

A fundamental question to the understanding of how individuals negotiate a complex environment with varying ground terrain is what specific types of surfaces and/or landmarks are fixated? Thus, the purpose of this study was to determine if people fixate surfaces they choose to eventually step on or surfaces they choose to avoid. The latter may be due to the fact that an individual considers a particular surface to be too large of a threat to stability based on prior experience or that it would cause a large deviation from the end goal. Additionally, what degree is the spatial layout of the environment surveyed such that the path is pre-planned (by fixating equally to all regions of the upcoming terrain) or that the route is determined on-line (by fixating specific sections of the terrain in a more sequential manner)?

## 3.3 Experimental procedures

### 3.3.1 Participants

Seven healthy young adults (3 female, 4 male; age range 18-30 yrs., mean ± SD age = 22.4 ± 4.5 yrs.) volunteered for this study. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behaviour in this study. Participants wore corrective lenses if necessary. The study was approved by the Office of

Research Ethics at the University of Waterloo and informed written consent was received from all participants.

### 3.3.2 Protocol

Participants were required to walk at a self-selected pace along a painted (medium shade of grey) wooden walkway (~8.5 m long, ~1.5 m wide and elevated ~0.1 m) where six different types of ground terrain (2 solid, 3 compliant, 3 rocky, 3 irregular, 3 tilt, and 1 slippery), each 0.5 m x 0.5 m, formed a 5 x 3 grid of 15 surfaces (i.e. multi-surface terrain section) in the middle portion (~2.5 m long) (see Fig. 3.1). The solid, tilt, and irregular surfaces were painted the same color as the walkway. The solid surfaces were constructed the same as the rest of the walkway and posed no challenge. The compliant surfaces were composed of medium-density foam (stiffness ~13 kN/m; maximum compression of ~0.08 m) and covered with a thin green fabric (to simulate wet, soggy, grass). The rocky surfaces were composed of a bed of small irregularly shaped rocks (ranging in size from 1x1.5 cm to 2x5 cm). The rocks were tightly packed similar to a gravel walk. The irregular surfaces had irregularly spaced custom-made dark grey rock-climbing holds mounted on the top. The height of these rock-climbing holds ranged from 1 to 3 cm and the spacing between holds ranged from 2 to 5 cm. The tilt (or uneven) surfaces were constructed such that they had a 10º downward tilt (either to the left or right in the frontal plane) and are referred to as Tilt – L or R. The slippery surface was made of a piece of white ultra-high molecular weight polyethylene (used for artificial ice in rinks) mounted on a wooden base. Each participant wore a full-body safety harness attached to a friction-less trolley (via a dynamic rock-climbing rope) mounted to an I-beam along the ceiling of the lab.

Participants performed four walking trials at the start of the experiment where the entire walkway consisted of a uniform solid surface (i.e. control walking) and walked to an end goal (see below). There were three different multi-surface terrain configurations in which participants had to walk across in subsequent walking trials. The three configurations were randomly constructed based on two factors: (1) there were 2 solid, 1 slippery, 3 compliant, 3 rocky, 3 irregular and 3 tilt surfaces available (chosen to represent commonly encountered ground terrain and fit the size of the experimental set-up and laboratory space available) for each configuration and (2) the rocky, compliant, and irregular surfaces were always grouped with their other two respective surfaces (see Figs. 3.1 and 3.4). A board obstructed the participant's view of the multi-surface terrain configuration prior to the start of each trial. Following a 'go' signal, the board obstructing the participant's view was removed and they began to walk such that they took around four steps before reaching the multi-surface terrain section (approximately 3 – 4 seconds). The path to walk across the multi-surface terrain was manipulated such that there were four conditions: (1) natural (no path restrictions in that participants were free to choose which surfaces to step on), (2) start left (start walking across the multi-surface terrain section at the leftmost column), (3) start center (start walking across the multi-surface terrain section in the middle column), and (4) start right (start walking across the multi-surface terrain section at the rightmost column). Two vertical posts were positioned on either side the appropriate surface of the first row of the multi-surface terrain configuration to denote the restricted path condition and participants were required to walk through them. Once past the posts, participants were free to choose which surfaces to step upon. However, irrespective of the conditions, participants were instructed to walk to an end goal marked with an 'x' on a piece of white paper mounted on the end of the walkway and visible throughout the trial. The four conditions were randomly presented within each configuration. Each block of trials of a particular configuration was repeated three times in random order. Only the first trial of each configuration and condition combination (i.e. a total of 12 trials per participant) was used in the analysis so that each potential path was somewhat novel and any influence from learning was avoided. To further avoid any influence from learning participants tested each surface (not in any specific configuration) prior to data collection by stepping on them so that they could experience the stability and characteristics of the surfaces.

### 3.3.3 Gaze fixation recording

Gaze fixations were recorded with an Applied Science Laboratories (ASL, Bedford, MA, USA) model 501 eye tracker mounted on the participant's head (weight under 227 g). This system has a precision better than 0.5º and spatial error less than 2º. Both pupil and corneal reflections from the left eye were captured to provide the line of sight (or fixation point) which was superimposed as a black square on the video image of the scene camera (mounted on the eye tracker on the person's head, which provided a view of what the individual 'sees'). The eye tracker was calibrated for each participant using a nine-point calibration procedure which required the person to fixate a series of nine points in a rectangular grid on the floor in front of them and was re-checked periodically throughout the testing procedure. A room camera (Panasonic Canada, Mississauga, Ontario, Canada) was positioned to capture a saggital view of the multi-surface terrain configuration. Video information of the eye, scene, and room camera were combined (see Fig. 3.1) using two digital mixers and recorded to DVD at 30 Hz.

### 3.3.4 Data and statistical analysis

Our results are divided into an approach phase, consisting of the time from the start of the trial to the first step on the multi-surface terrain section and a multi-surface phase, consisting of the first step on the multi-surface terrain section until stepping off the last surface (as determined from the video data).

Frame-by-frame analysis of the combined video data was completed for each participant to identify gaze fixations throughout the trials (Patla and Vickers, 1997, 2003). A fixation was defined as gaze stabilized on a location for three consecutive frames (~100 ms) or longer (Patla and Vickers, 1997, 2003). An average of 0.27 % of fixations among the participants were considered travel gaze fixations and not included in the analysis. A travel gaze fixation involves the eyes fixating in front of the individual and being carried along by the moving individual (Patla and Vickers, 1997).

Fixations to the following locations were identified: solid, slippery, irregular, rock, compliant, and tilt surfaces, transition region between two different surfaces (transition-2), transition region between three/four different surfaces (transition-3/4), end goal, areas before (pre) and after (post) the multi-surface terrain section, and all other locations (other). The transition region represented the region between different surfaces and was determined based on the position of the black cursor superimposed on the video. Specifically, a fixation was directed to a transition region if the cursor was directly on the transition point or on either side of it but within a space equivalent to the size (see Fig. 3.1b,c) of the black cursor. The determination of the location of fixation (to a surface and/or transition region) was based on visual identification of the position of the black cursor; the accuracy was periodically checked by another person blinded to the study.

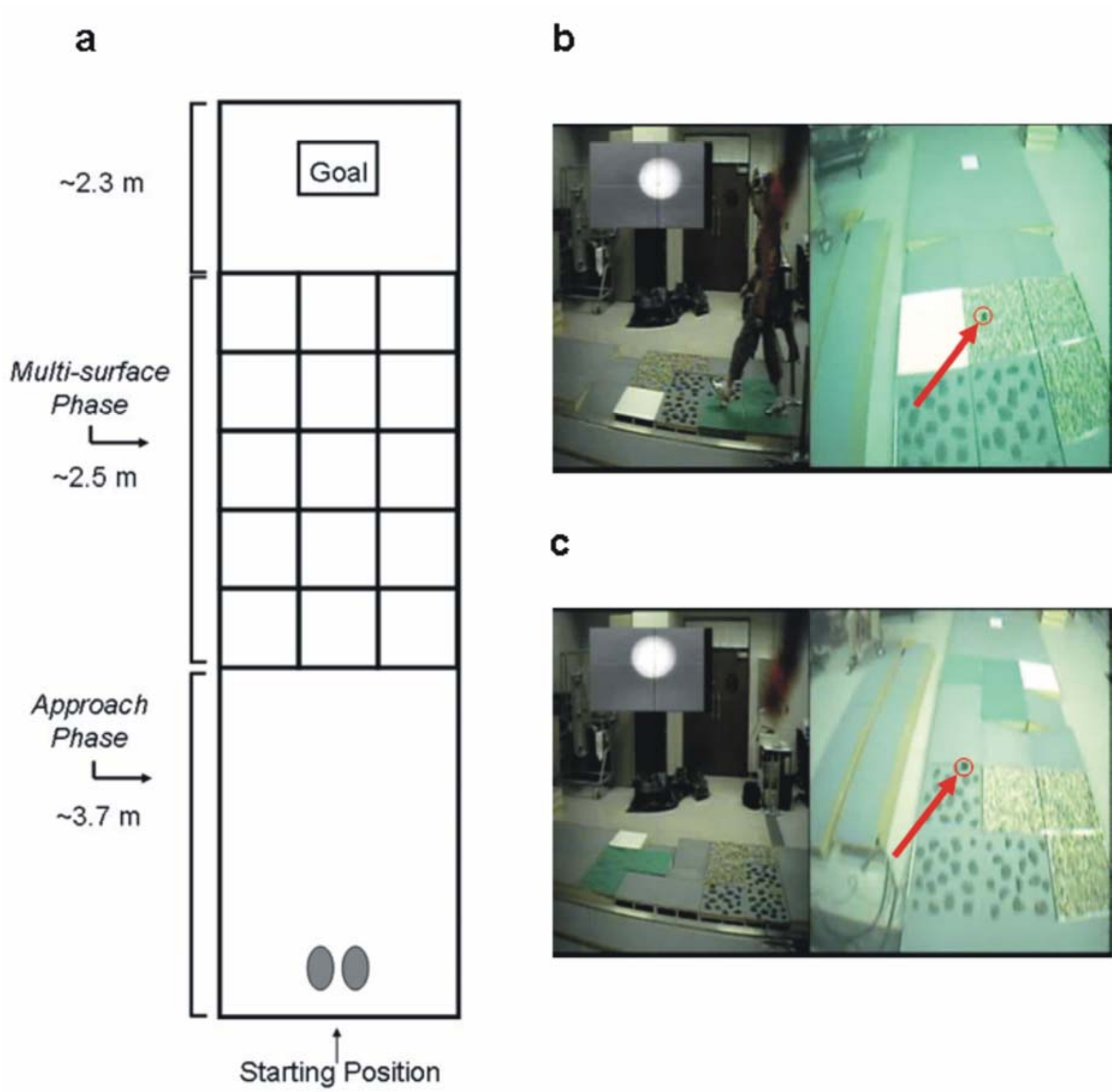



**Figure 3.1**: Experimental set-up. (a) The walkway with the multi-surface terrain section. The approach and multi-surface phases are also shown. Video information of the eye, scene, and room camera were combined and single frame examples are shown illustrating a fixation (denoted by the arrows and circles) to a (b) surface and (c) transition region. The eye is the white circle in the top left corner of each single frame image. The scene view (from a camera on the participant's head) is shown on the right side of the split-screen and a room camera showing a sagittal view of the multi-surface terrain configuration is shown on the left side.

For the analysis of fixation location, fixations among the three restricted path conditions (i.e. start left, center, and right) within a particular multi-surface terrain configuration were pooled. Subsequently the fixations for this condition along with the natural condition (i.e. free to choose path) were normalized to correct for the different probability of fixating on a particular surface or transition region. Normalization was accomplished by dividing the number of fixations to each surface or transition region by the number of possible surface locations or transition regions of the same type available to fixate within a particular configuration. This normalization procedure is important, for example, because there are more transition-2 regions than transition-3/4 regions (and there are more total transition regions compared to surface regions) available to fixate. As another example, there is only one slippery surface compared to two or three surfaces of the other types. Fixations across the different configurations were then pooled to determine a normalized mean number of fixations to a particular location. The rationale for examining the frequency of fixations to a particular location was based on the assumption that an increase in frequency of fixations is due to the increased importance of that location to perform the task. Multiple fixations to a similar area would be important to acquire appropriate and sufficient visual information and fixations made at different vantage points along the multi-surface terrain would allow this information to be integrated for safely traversing the complex ground terrain.

The first step in the analysis was to determine task-relevant fixations. A task-relevant fixation was defined as a fixation directed to a surface (or transition region) that was eventually stepped on (i.e. the participant stepped on the surface panel within which the fixation was located) as the participant crossed the multi-surface terrain section. If a fixation was directed to a transition region and the participant stepped on one of the two (three, or four) surfaces that the transition region covered then it was considered a task-relevant fixation. For both the approach and multi-surface phases a two-way ANOVA with condition (natural vs. restricted) and location (area stepped on vs. area not stepped on) as the within-subject factors was performed.

Subsequently, we compared fixations among the six different surfaces using a two-way ANOVA with condition (natural vs. restricted) and location (solid, slippery, irregular, rocks, tilt, and compliant) as the within-subject factors for both the approach and multi-surface phases. Next, we compared the normalized mean number of fixations for the surface (all surfaces combined) versus transition regions (transition-2 and transition-3/4 locations). This entailed a two-way ANOVA with condition (natural vs. restricted) and location (surface total vs. transition total) as the within-subject factors for both the approach and multi-surface phases. We then compared fixations to transition-2 with transition-3/4. This was done using a two-way ANOVA with condition (natural vs. restricted) and location (transition-2 vs. transition-3/4) as within-subject factors for both the approach and multi-surface phases.

To determine whether fixations were used to scan the entire layout or rather just certain sections of the multi-surface terrain configuration, the percent of fixations directed to the first two rows of the multi-surface terrain (including all transition regions) was calculated and compared to the percent of fixations directed to the last two rows of the multi-surface terrain section (including all transition regions) for the approach phase. A two-way ANOVA was then performed with condition (natural vs. restricted) and cluster (first two rows vs. last two rows) as within-subject factors. Approximately 95 % of fixations were directed to the last two rows during the multi-surface phase and thus no statistics were performed for this phase.

An alpha level of 0.05 was chosen for significance for all statistical analyses. The data were rank or arcsine transformed where appropriate if the data was not normally distributed (as determined by examination of normality plots and the Shapiro-Wilk test).

### 3.4 Results

The mean number of fixations made during the control walking and multi-surface walking trials were 11.5 ± 2.2 and 18.3 ± 3.3, respectively (paired t-test, $P < 0.05$). During the multi-surface walking trials 91.1 ± 10.3 % of fixations were directed to the multi-surface terrain compared to only 55.8 ± 22.7 % (paired t-test, $P < 0.05$) of fixations directed to the equivalent location (i.e. the uniform solid surface where the different surfaces were present in the multi-surface walking trials) for the control walking trials.

Visual information from the surfaces that one eventually steps on is critical to ensure proper foot placement and to maintain balance. As such, we determined the average number of fixations directed to task-relevant surfaces in both the approach and multi-surface phases. Clearly illustrated in Fig. 3.2 is the fact that fixations are predominantly directed to surfaces that are stepped on (i.e. task-relevant). This is evident from fixations made during both the approach (ANOVA main effect: $F_{1,6} = 34.03$, $P = 0.001$) and multi-

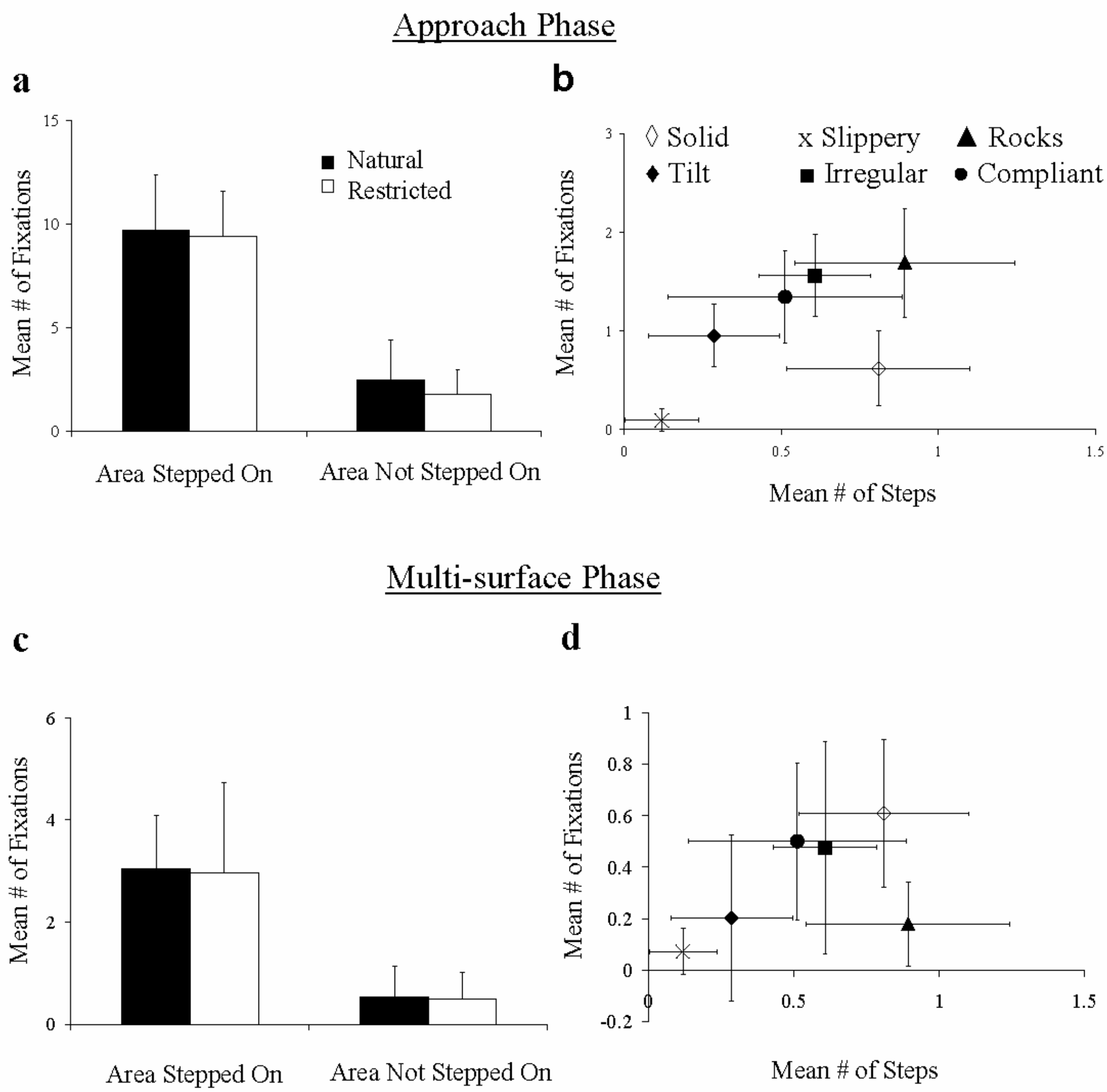



**Figure 3.2**: Task-relevant fixations (N = 7 participants). Mean number of fixations directed to an area (i.e. surface or transition region) that was eventually stepped on compared to an area that was not stepped on for both the (a) approach and (c) multi-surface phases. Also shown are scatter plots for the (b) approach and (d) multi-surface phases showing the number of fixations and steps per trial averaged across participants. Error bars represent standard deviation.

surface phases (ANOVA main effect: $F_{1,6} = 69.01$, $P = 0.0002$). During the approach phase, only 12.3 ± 8.4 % and 7.3 ± 4.4 % of the task-relevant fixations (i.e. area stepped on) for the natural and restricted path conditions, respectively, were fixations to the transition-3/4 region. During the multi-surface phase only 5.4 ± 6.9 % and 3.9 ± 5.3 % fixations for the natural and restricted path conditions, respectively, were fixations to the transition-3/4 region.

The scatter plots in Fig. 3.2b and 3.2d illustrate the relationship between surfaces fixated and surfaces stepped on. The number of fixations and steps per trial are averaged across the participants for both the approach and multi-surface phases. As the frequency of fixations to a particular surface increases so does the frequency of stepping on it. Note that during the approach phase (Fig. 3.2b) there are few fixations to the solid surface but participants frequently stepped on them later. In contrast, during the multi-surface phase (Fig. 3.2d) the solid surfaces are fixated to a much greater extent.

An important question is which surfaces or aspects of the multi-surface terrain are actually fixated and provide useful visual information to negotiate the difficult terrain? The normalized mean number of gaze fixations directed to the different locations/landmarks of the walkway is illustrated in Fig. 3.3. We first asked which particular surface was fixated more frequently, if any. Indeed, certain surfaces were fixated more than others for the both the approach (ANOVA main effect: $F_{5,30} = 7.04$, $P < 0.0002$) and multi-surface phases (ANOVA main effect: $F_{5,30} = 3.86$, $P = 0.0008$) as illustrated in Fig. 3.3. Duncan's post-hoc test showed that the rocks, irregular, and compliant surfaces were fixated more frequently during the approach phase compared to the other surfaces with the slippery surface fixated the least. During the multi-surface phase, Duncan's post-hoc test demonstrated that the solid surface was fixated to a greater extent than the slippery, tilt, and rocky surfaces.

Next, we compared fixations directed to a surface (solid, slippery, irregular, rocks, compliant, tilt surfaces combined) with fixations to a transition region (transition-2 and transition-3/4 combined). For the approach phase, there was a significant interaction (ANOVA: $F_{1,6} = 7.09$, $P = 0.037$). In addition, there was a significant location main effect (ANOVA: $F_{1,6} = 21.98$, $P = 0.003$) showing a greater number of fixations to surfaces than transitions. For the multi-surface phase, fixations were directed more frequently to an

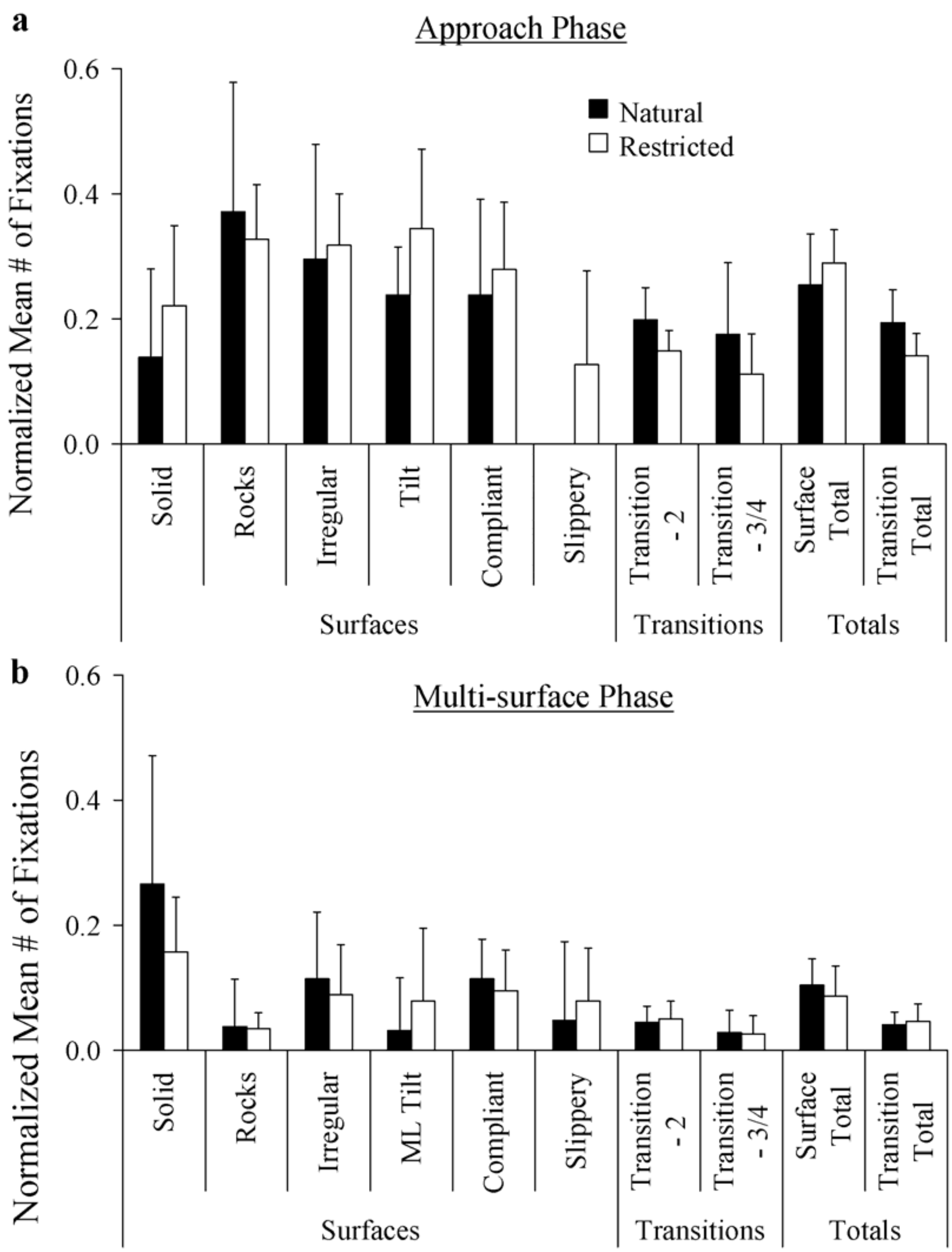


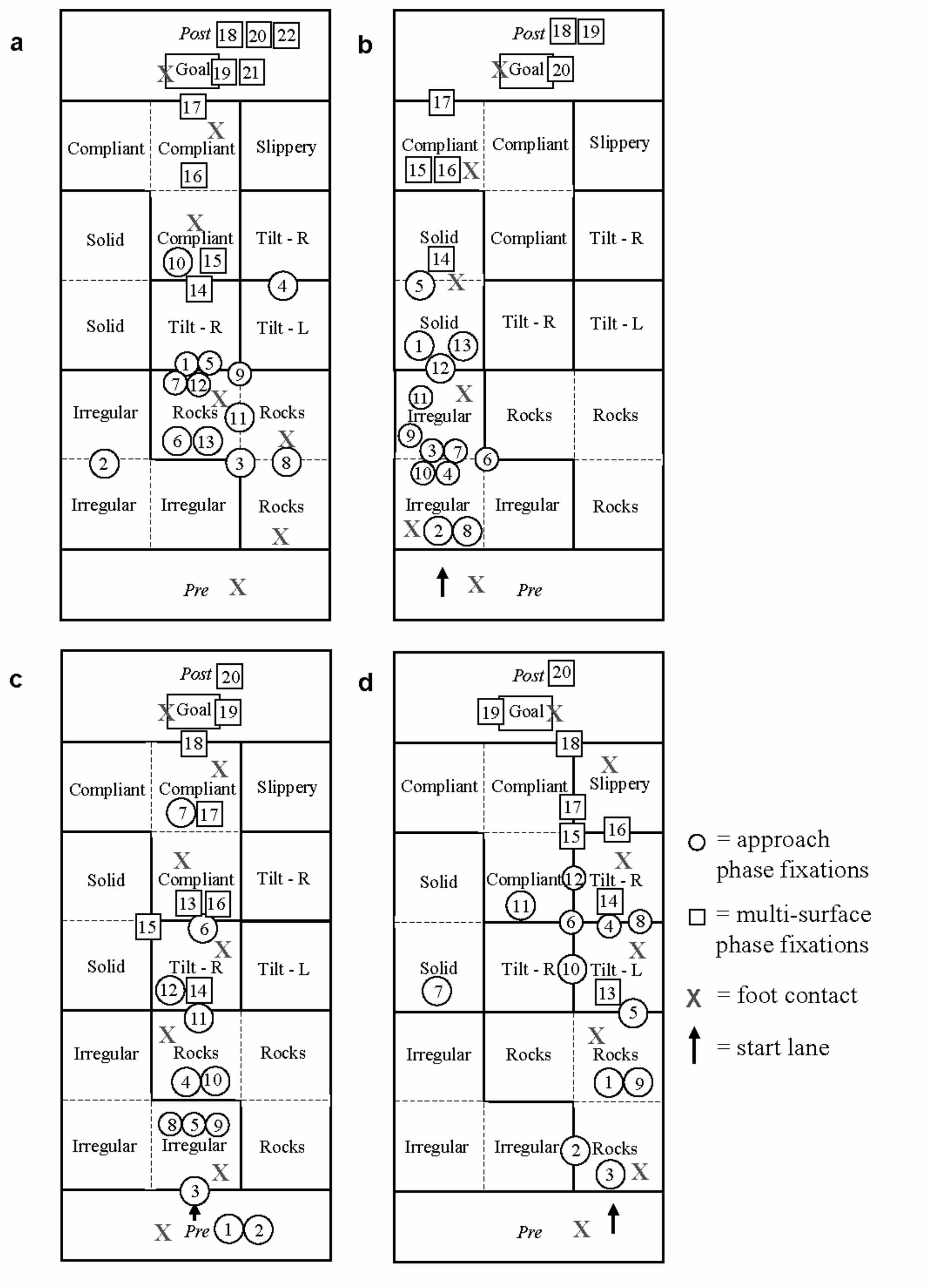

**Figure 3.3**: Gaze fixation locations (N = 7 participants). Normalized mean number of fixations directed to a particular surface or transition region for both the (a) approach and (b) multi-surface phases. Error bars represent standard deviation. Normalization involved dividing the number of fixations by the number of available locations for each surface and transition type before calculating the mean number of fixations.

actual surface compared to a transition region (ANOVA main effect: $F_{1,6} = 25.93$, $P = 0.002$).

Finally, we asked which transition region was fixated more frequently (transition-2 or transition-3/4). There was no significant interaction (ANOVA: $F_{1,6} = 0.13$, $P = 0.732$) or main effects (ANOVA – condition main effect: $F_{1,6} = 3.78$, $P = 0.100$; ANOVA – location main effect: $F_{1,6} = 1.34$, $P = 0.291$) for the approach phase (see Fig. 3.3). However, there was a main effect of location for the multi-surface phase (ANOVA main effect: $F_{1,6} = 7.41$, $P = 0.035$) with a greater number of fixations directed to transition-2 compared to transition-3/4.

What is clear from the results is that people rarely fixated the slippery surface, possibly due to the perceived threat of this surface, which is reflected in the low frequency of actually stepping on it while negotiating the multi-surface terrain. When stepping on the tilt surfaces, participants predominantly stepped on the minimally tilted portion close to ground level rather than on the aspect substantially below ground level. In fact, in terms of where people actually stepped when traversing the multi-surface terrain section, 22.9 % of steps were on the rock surfaces compared to 20.7 % on the solid surfaces, 15.5 % on the irregular surfaces, 14.6 % on the transition region between two different surfaces, 13.1 % on the compliant surfaces, 7.3 % on the tilt surfaces, 3.0 % on the slippery surface, and 2.7 % on the transition region between three/four different surfaces. Thus, approximately 83 % of steps were onto actual surfaces whereas only 17 % of steps were made onto a transition region.

If gaze fixations during the approach phase are clustered predominantly to the first two rows of surfaces and during the multi-surface phase are clustered to the last two rows of surfaces this would suggest a form of on-line control whereby spatial information is obtained sequentially and may be stored and updated continuously as one traverses the varying ground terrain. In this sense, the decision as to which surface to step on might be made closer to the time the person is approaching that surface rather than visually sampling the entire multi-surface terrain and pre-planning the entire route. As can be seen from data of one individual (and one multi-surface terrain configuration) exemplified in Figs. 3.4 and 3.5, fixations during the approach phase are directed to the first few rows of surfaces of the multi-surface terrain section. During the approach phase $63.2 \pm 14.3$ % of fixations are



a
Post 18 20 22
Goal 19 21
17
Compliant
Compliant
Slippery
16
Solid
Compliant
Tilt - R
10 15
14
4
Solid
Tilt - R
Tilt - L
Irregular
Rocks
Rocks
Irregular
Irregular
Rocks
Pre
b
Post 18 19
Goal 20
17
Compliant
Compliant
Slippery
15 16
Solid
Compliant
Tilt - R
14
Solid
Tilt - R
Tilt - L
Irregular
Rocks
Rocks
Irregular
Irregular
Rocks
Pre
c
Post 20
Goal 19
18
Compliant
Compliant
Slippery
7 17
Solid
Compliant
Tilt - R
13 16
15
Solid
Tilt - R
Tilt - L
12 14
11
Irregular
Rocks
Rocks
Irregular
Irregular
Rocks
Pre
d
Post 20
19 Goal
18
Compliant
Compliant
Slippery
17
15
16
Solid
Compliant
Tilt - R
14
Solid
Tilt - R
Tilt - L
13
Irregular
Rocks
Rocks
Irregular
Irregular
Rocks
Pre
= approach phase fixations
= multi-surface phase fixations
X = foot contact
= start lane

**Figure 3.4**: Sample of gaze fixations made by one individual for one particular multi-surface terrain configuration. Fixations are shown for the (a) natural condition, (b) start left condition, (c) start center condition, and (d) start right condition as denoted by the arrows. Fixations made during the approach phase are indicated by the circles and fixations made during the multi-surface phase are indicated by the squares. The numbers within the circles and squares corresponds to the temporal sequence of fixations. Foot contacts (i.e. steps made while traversing the multi-surface terrain) are shown as X's. The position of the foot contacts in this figure are not precise locations (i.e. they do not represent the exact position) but rather denote the surface stepped on or the approximate location of the transition region stepped on. The dashed lines within the multi-surface terrain section illustrates that while different blocks of the surface are used to form the grid, the surfaces are the same and thus do not represent a transition region between surfaces. In this example, there were 40 fixations to surfaces compared to 28 fixations directed to transition regions among the four conditions (including only fixations made to the multi-surface terrain).

directed to the first two rows compared to only 21.8 ± 14.9 % to the last two rows (ANOVA main effect: $F_{1,6} = 16.46$, $P = 0.007$). In contrast, 94.5 ± 6.4 % of fixations during the multi-surface phase are directed to the last two rows. A more detailed description of fixations directed to the rows of the multi-surface terrain is illustrated in Fig. 6. While the mean fixation duration for fixations directed to the front and back rows was not different (back rows = 240.9 ± 48.8 ms versus front rows = 265.2 ± 48.3 ms, $P > 0.05$) the total sampling duration was significantly longer ($P < 0.05$) for fixating the front rows (23.8 ± 9.7 seconds) versus the back rows (6.3 ± 2.6 seconds).

The path restrictions/instructions also influenced the gaze fixation pattern (see Fig. 3.4). When no path restrictions were imposed fixations were spread around the multi-surface terrain section compared to a cluster of fixations along the column that the individual was instructed to start in the restricted conditions. Specifically, in the start left condition 90.4 ± 5.5 % of fixations were directed to the left column, in the start center condition 89.8 ± 9.3 % of fixations were directed to the center column, and in the start right condition 78.6 ± 17.6 % of fixations were directed to the right column. In contrast, in the natural condition 26.5 ± 13.0 %, 59.0 ± 13.3 %, and 14.5 ± 15.2 % of fixations were directed to the left, center, and right columns, respectively. These results suggest that individuals do not evoke a visual search of the entire multi-surface terrain section but rather their fixation patterns indicate a more systematic top-down approach.

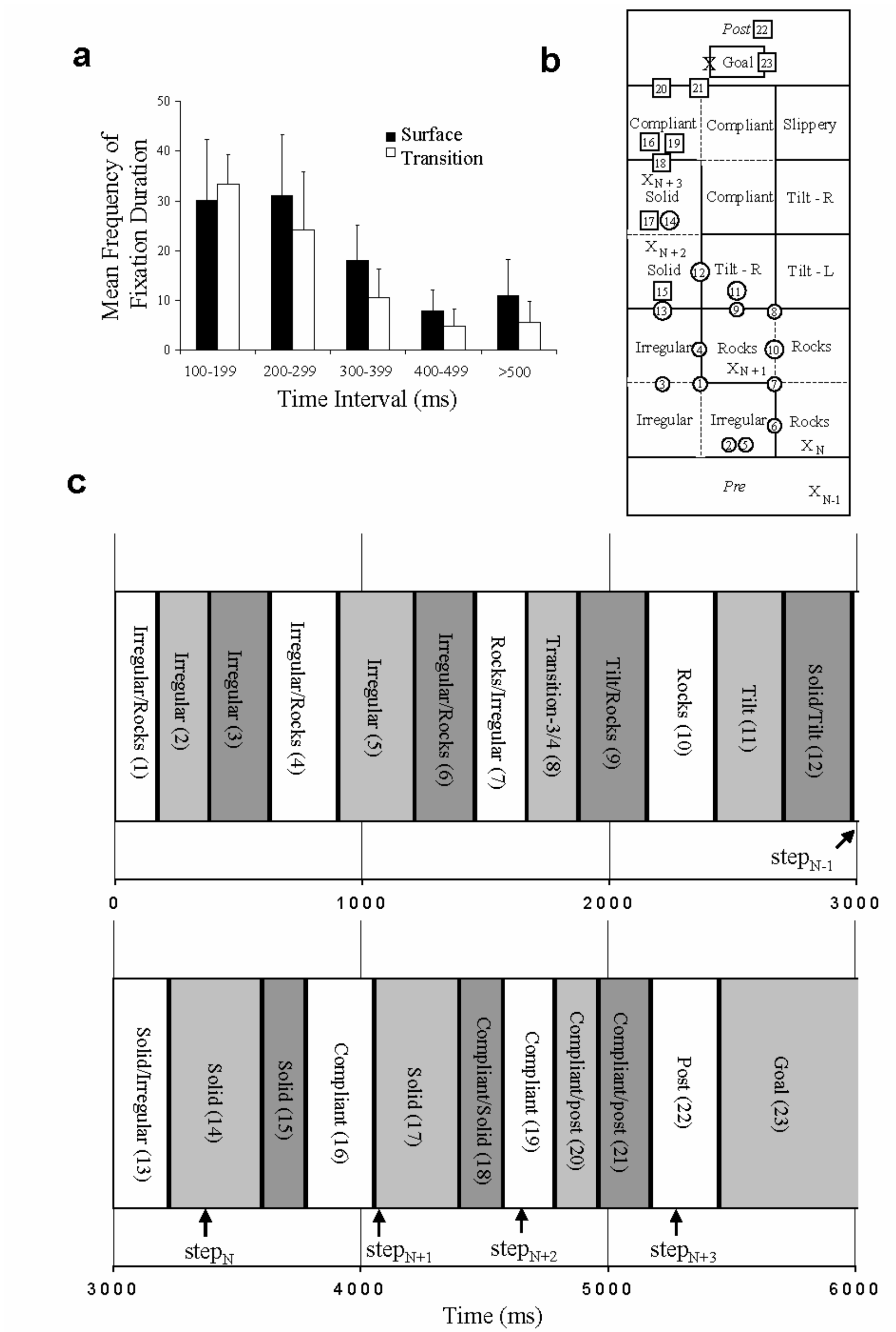



**Figure 3.5**: Spatio-temporal analysis of gaze fixations. (a) Mean frequency of fixation duration for intervals of ~100 ms for the entire sample (N = 7 participants). Error bars represent standard deviation. Spatio-temporal relationship of gaze fixations for one representative trial of one participant is shown in (b) and (c). Fixations made during the approach phase are indicated by the circles and fixations made during the multi-surface phase are indicated by the squares. The numbers within the circles and squares correspond

to the temporal sequence of fixations. Foot contacts (i.e. steps made while traversing the multi-surface terrain) are shown as X's with their corresponding step number (e.g. N+1). The numbers in (c) correspond to the fixation number in (b). Black shaded bars in (c) represent saccades.

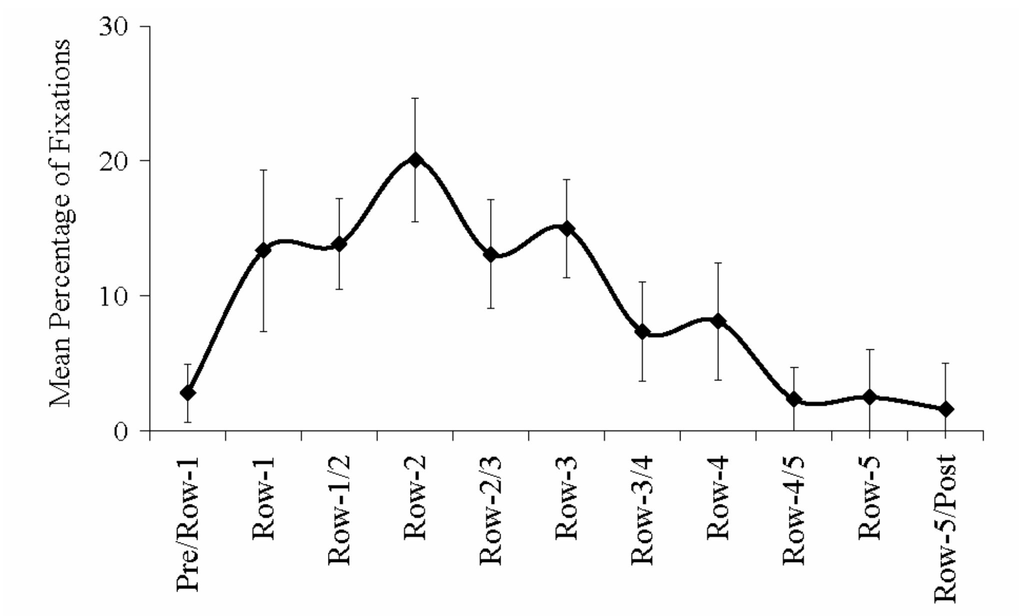



**Figure 3.6**: Distribution of fixations based on the row of the multi-surface terrain configuration. Mean percentages of fixations directed to each multi-surface terrain row are shown along with the standard deviation (see error bars).

The fixation numbers in Fig. 3.4 demonstrate the temporal sequence of fixations. The spatio-temporal relationship of gaze fixations is shown in greater detail in Fig. 3.5. Fixation durations were mainly between 100-300 ms (see Fig. 3.5a). Similar to Fig. 3.4, the temporal sequence of fixations is shown for one representative trial of one participant in Fig. 3.5b. The spatio-temporal relationship of gaze fixations for this trial is shown in Fig. 3.5c. Examination of the temporal relationship between fixations and stepping (for the step immediately preceding the multi-surface terrain section and the two subsequent steps on the different surfaces) demonstrated that ~56% of the time individuals fixate approximately two steps ahead. This corresponds to look ahead fixations of approximately 1200 ± 110 ms (see Fig. 3.5 panel b and c for an example).

### 3.5 Discussion

We sought to investigate the role of vision for negotiating varying ground terrain. The results clearly illustrate how visual information is sampled to guide foot placement and path selection and provides the first step towards understanding the complex nature of maintaining balance and safely traversing an environment with unstable ground terrain.

Previous work has shown that when stepping onto irregularly placed targets while walking or when approaching an obstacle to step over, the dominant fixation behaviour (i.e. travel gaze fixation) involves the eyes visually anchored in front of the moving individual and being carried along as that individual progresses forward (Patla and Vickers, 1997, 2003). This type of gaze behaviour (referred to by the authors as constant gaze episodes) is also found in cats when walking in a cluttered environment (Fowler and Sherk, 2003). However, in an environment with enriched visual features such as in the present experiment, this type of behaviour may not be appropriate. In fact, travel gaze fixations were essentially non-existent (i.e. < 1% of fixations) when approaching and traversing the multi-surface terrain. Instead, the eyes were actively moved in order to fixate on critical landmarks of the ground terrain. Further support for the importance of active gaze stems from the fact that both the fixation frequency and percent of fixations directed to the region where the different surfaces were located (or equivalent area in the control walking trials) are greater when walking on the multi-surface terrain compared to walking on the uniform surface. Thus, as the ground terrain becomes more challenging the passive nature of travel gaze fixations become less beneficial and more active fixation strategies are required. Wilkie and Wann (2003) have shown during a steering task that active (or free) gaze results in better performance over a fixed gaze condition.

As with previous studies, we found individuals fixate predominantly on task-relevant areas (Ballard et al. 1992; Land and Hayhoe, 2001; Land and Lee, 1994; Land et al. 1999; Pelz and Canosa, 2001). Specifically, people fixate on the surface they will eventually step onto. This is similar to the ‘do it where I’m looking’ strategy of Ballard et al. (1992) for a block-copying task and suggests that task requirements, in part, dictate where to fixate. This strategy of a tight coupling between fixations and task-relevant surfaces also infers that top-down processes, in part, guide fixation patterns and is further evident in the influence of path restriction on gaze fixation patterns. Specifically, the clustering of fixations was tightly clustered to the column of surfaces when the travel path was restricted such that fixations were predominantly directed to the left column in the start left condition or were directed to the right column in the start right condition. Yarbus (1967), in a task involving the studying of a painting, showed how task instruction influenced fixation patterns and revealed how the goal of the task is linked with eye movements.

What locations of the environment were fixated and thus critical for negotiating the ground terrain? While individuals often stepped on the solid surfaces they rarely fixated them during the approach phase. This may have been due to the fact that the solid surfaces contain relatively little salient visual information compared to the other surfaces where the characteristics (e.g. irregularities and unevenness) may be more important for maintaining balance. However, while walking on the multi-surface terrain section the solid surfaces were frequently fixated presumably to guide foot placement. When traversing on or around the tilt surfaces fixations were often directed to the transition region. This may have been due to the fact that the slope of the tilt surface makes a portion of the tilt surface below the level of the walkway and thus an obstacle is created as the subsequent ground terrain is elevated in comparison to the slope (see Fig. 3.1) and results in a greater challenge. While fixations to actual surfaces were indeed more prevalent, gaze fixations were frequently made to transition regions between two different surfaces. This is despite the fact that there were more possible fixation locations for transition regions compared to surfaces yet, it is also noteworthy to mention that the surface regions make up more total surface area of the multi-surface terrain.

What salient information would fixation on the transition region between different surfaces provide? The fact that fixations are frequently made to transition regions is not surprising, as there is evidence from monkeys (Lamme et al. 1999; Lee et al. 1998; Rossi et al. 2001; von der Heydt et al. 2000) and humans (Kastner et al. 2000) that neurons in visual areas (such as V1, V2, and V4) are sensitive to texture boundaries and contrast edges.

Fixating on the transition regions around a particular surface can provide length and width information and thus allow targeting of a step onto the surface or avoidance of a potentially destabilizing or threatening surface. We found several instances of both cases. Additionally, fixating the transition between surfaces allows the brain to covertly attend to both surfaces. This latter explanation would provide the CNS with a greater amount of information. Alternatively, the parafoveal region (rather than the fovea) may still be able to obtain detailed visual information from the multiple surfaces around the transition region. By directing attention to multiple surfaces, details of each may be integrated into a more global spatial map to determine the relationship between surfaces (e.g. distance) and subsequently aid in planning additional steps. Knowing the surrounding areas is critical if a step onto a particular surface proves too challenging and rapid re-adjustment in the path taken needs to be implemented. Only 17 % of steps across the varying ground terrain were made onto a transition region despite the large percentage of fixations directed to these regions during both the approach and multi-surface phases. This supports our contention that fixations on a transition region are more related to gathering greater amounts of information about the terrain characteristics and layout rather than for guiding precise foot placement.

While visually scanning (through visual search routines) the entire layout of approaching ground terrain enables the visual system to extract necessary information to pre-plan the complete travel path, our evidence seems to argue against this notion. During the approach phase 63 % of fixations were directed to the first two rows of the multi-surface terrain section compared to only 22 % to the last two rows. In contrast, almost 95 % of fixations during the multi-surface phase were directed to the last two rows. In addition, when we examined the temporal relationship between fixations and stepping (for the step immediately preceding the multi-surface terrain section and the two subsequent steps on the different surfaces) we found that individuals fixate approximately two steps ahead (~ 56 % of the time), which corresponds to look ahead fixations of approximately 1.2 ± 0.11 seconds. Previous research has also shown people fixate approximately two steps ahead (or 0.8-1.0 seconds) when targeting irregularly spaced footprints on the ground (Patla and Vickers, 2003). However, this was a relatively simple task in comparison. While steering during driving, fixations to locations ahead also occur ~1-2 seconds in advance

(Land and Horwood, 1995; Land and Lee, 1994; Wilkie and Wann, 2003). In cats, Wilkinson and Sherk (2005) have recently found that visual input provides enough information of a cluttered environment for the cats to make between one and four accurate steps (i.e. stepping into irregularly spaced holes). Interestingly, people are able to implement avoidance strategies and direction changes if visual information is obtained at least two steps ahead (Patla, 1997). Thus, layout information and characteristics of the surfaces may be stored for two or three steps and be continually updated on-line through additional fixations and/or peripheral vision.

Fajen and Warren (2003) have recently modeled the visual control of locomotion for steering and avoiding obstacles using a behavioural dynamics approach. They argue that the path an individual chooses emerges in an on-line fashion based on the responses to visually specific goals (attractors) and obstacles (repellers) as the person interacts with the environment (Fajen and Warren, 2003). Applied to the present task, certain surfaces such as the rocks and solid surfaces (as well as the end goal) might act as attractors guiding locomotion. In contrast, other surfaces such as the slippery and tilt surfaces (and the walkway's physical boundaries) might act as repellers, which would steer the person away from stepping on or near those areas.

However, a portion of the time between fixating a particular surface and stepping on it (the approximately 1.2 seconds of the look ahead fixations) may be used to generate an internal model. Indeed, individuals can spatially and temporally integrate visual information from separate fixations in order to build an internal construct of the environment – a process known as transsaccadic integration (Hayhoe et al. 1991; Prime et al. 2006). Parietal area 5, which receives input from visual centres and provides output to the motor cortex and spinal cord, may integrate information about the heterogeneity of the ground terrain during walking as evident from the fact that activity of neurons in this area in cats is different between a ladder walking task where the surface was homogeneous compared to both ladder walking with a visually heterogeneous surface and flat walking (Beloozerova and Sirota, 2003). Therefore, discharges of neurons in regions of the parietal cortex may facilitate appropriate adjustments of stepping onto varying ground terrain. The strategy of creating an internal model of the layout of the ground terrain is particularly effective in that it ensures the CNS can respond to unexpected events in the travel path (for example, an unseen hole in the ground). This CNS visuo-motor processing would complement local mechanical and neuromuscular reflex responses involved in adjusting for different ground terrain (Marigold and Patla 2005).

In conclusion, the eyes are actively moved such that gaze fixations while negotiating complex ground terrain are directed in an on-line and highly task-relevant manner to specific features of the environment. Furthermore, fixations are often directed to the transition region between different surfaces, which allows the nervous system to obtain and integrate a greater amount of visual information to safely perform the task.

### 3.6 Bridging summary

This study provides a baseline of the characteristics of gaze fixation patterns for young adults, which allows for a comparison with older adults to determine the influence of aging. The key findings from this study were that young adults fixate highly task-relevant areas (i.e. surface blocks eventually stepped on) in an on-line manner. The following experiment attempted to determine how healthy aging affects these strategies.

# CHAPTER 4 - Influence of aging on gaze fixation patterns while negotiating varying ground terrain

## 4.1 Abstract

Visual information provides the nervous system with details of the environment as well as time to adapt to any challenges ahead. Age-related changes in visual function are common and increase the risk of falling. Thus, it is important to understand how older adults negotiate complex environments with the hope of preventing falls in the future. The aim of this study was to determine whether normal healthy aging influences gaze fixation patterns for negotiating varying ground terrain. We had seven healthy older adults walk across a walkway with varying ground terrain while gaze fixations were monitored. We also used a sample of seven young adults from a previous study to investigate changes of gaze fixation patterns with aging. Gaze fixation patterns of the older adults were similar to the young adults. Gaze fixations were directed in a highly task-relevant manner in that older adults predominantly fixated on areas eventually stepped on. There were no differences in the duration of fixations between young and older adults. These results suggest that healthy aging does not influence gaze fixations patterns while negotiating varying ground terrain.

## 4.2 Introduction

Ground terrain continually changes when walking outside. Safe travel requires information about surface characteristics in order for the central nervous system to adjust and maintain stability. Visual information is critical in this regard as it provides the nervous system with details of the environment as well as time to adapt to any challenges ahead. Gaze fixation patterns of young adults walking across varying ground terrain demonstrate that the eyes are actively moved, rather than passively carried along with the moving observer in more simpler tasks (Patla et al. 1997, 2003), such that they are directed to highly task-relevant features of the environment (i.e. surfaces eventually stepped on) (Marigold and Patla 2007). Furthermore, gaze fixations are often directed to a transition region between two different surfaces presumably to acquire a greater amount of information to aid in guiding foot placement (Marigold and Patla 2007).

Age-related changes in visual function are reflected by a decline in the useful field of view, decreased contrast sensitivity, reduced depth perception, and a modest attenuation of visual acuity (Black and Wood 2005; Haegerstrom-Portnoy et al. 1999; Owsley et al. 1995; Watson 2001). These visual impairments as well as age-related visual conditions such as macular degeneration, glaucoma, cataracts and diabetic retinopathy all increase the risk of falling in older adults (Black and Wood 2005; Coleman et al. 2004; Harwood 2001; Lord and Dayhew 2001; Tinetti et al. 1988). Considering the fact that about one-third of older adults aged 65 years and over fall at least once a year, nearly half of which fall multiple times, and falls and related injuries are independent determinants of functional decline, this highlights the importance of understanding why older adults fall (Lord and Dayhew 2001; Tinetti et al. 1988; Tinetti and Williams 1998). Visual field loss associated with aging is also related to a decline in mobility: walking speed decreases and individuals are more likely to bump into obstacles or other objects (Patel et al. 2006; Turano et al. 2004). Furthermore, poor visual attention as measured by processing speed on the useful field of view test is also a risk factor for bumping into objects while walking (Broman et al. 2004).

Recently, Chapman and Hollands (2006) have shown that older adults require vision at particular times during the step cycle to pre-plan future steps onto certain targets in the travel path: foot placement error and task failure rates are increased compared to young adults when vision is removed at key time points. Few studies, though, have examined gaze fixations among older adults while walking. Older adults initiate downward saccades earlier than young adults with respect to foot-lift when stepping onto a raised platform (Di Fabio et al. 2003a). Furthermore, older adults fixate downward longer than young adults prior to stepping over an obstacle in the travel path (Di Fabio et al. 2003b). In addition, the frequency of downward saccades of high-risk cognitively challenged older adults while stepping over an obstacle is reduced and they are slower to respond (i.e. initiate a downward saccade to the obstacle) to a complex visual cue (Di Fabio et al. 2005). More recently, Chapman and Hollands (2005) demonstrated that older adults look earlier to stepping targets and spend a greater amount of time fixating them than young adults. The results of these studies suggest that older adults may require greater visual processing time for acquiring details of the environment, which may be related to slowed cognitive processing ability (Salthouse 1996) and/or poor visual function.

The aim of this study was to determine whether normal healthy aging influences gaze fixation patterns for negotiating varying ground terrain. In particular, we were interested in whether older adults fixate longer on features of the environment during this complex walking task. Furthermore, we asked the question of whether older adults direct gaze fixations to the entire layout of the upcoming environment to facilitate path planning ahead of time or whether fixations are directed to specific sections of the terrain as they walk similar to young adults.

## 4.3 Methods

### 4.3.1 Participants

Seven healthy older adults (3 female, 4 male; age range 62-74 yrs., mean ± SD age = 65.1 ± 4.4 yrs.) volunteered for this study. In order to determine the influence of aging, seven healthy young adults (3 female, 4 male; age range 18-30 yrs., mean ± SD age = 22.4 ± 4.5 yrs.) from a previous study (Marigold and Patla 2007 or Chapter 3) were included. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behaviour in this study. Participants wore corrective lenses if necessary. However, no participants wore multi-focal lenses. Visual testing consisting of binocular visual acuity and binocular contrast sensitivity were performed using a Bailey-Lovie type logMAR chart read at 6.3 meters (and thus providing a range of 0.8 to -0.5 log MAR) and a Pelli-Robson contrast sensitivity chart read at 1 meter, respectively. Balance confidence, functional mobility, and visuomotor processing ability were assessed using the Activities-specific balance confidence (ABC) scale (Powell and Myers 1995), timed up and go test (Podsiadlo and Richardson 1991), and the Trail Making Test (part A and B) (Tombaugh 2004), respectively, to provide an overall picture of the abilities of the young and older adults (see Table 4.1).

The study was approved by the Office of Research Ethics at the University of Waterloo and informed written consent was received from all participants.

**Table 4.1:** Participant characteristics.

| **Characteristics*** | **Young Adults (N = 7)** | **Older Adults (N = 7)** |
|---|---|---|
| **Age, years** | 22.4 ± 4.5 (18 - 30) | 65.1 ± 4.4 (62 - 74) |
| **Gender, Male/Female** | 4/3 | 4/3 |
| **Binocular Acuity, logMAR** | -0.3 ± 0.1 (-0.4 to -0.2) | 0 ± 0.2 (-0.2 to 0.2) |
| **Binocular Contrast Sensitivity, log** | 1.7 ± 0.1 (1.65 - 1.8) | 1.5 ± 0.1 (1.35 - 1.5) |
| **Timed Up and Go, seconds** | 8.1 ± 1.1 (6.0 - 9.3) | 7.5 ± 0.3 (7.2 - 9.4) |
| **ABC scale, %** | 90.5 ± 8.8 (76.9 - 99.4) | 95.8 ± 3.8 (90.0 - 100) |
| **Trail Making Test A, seconds** | 18.8 ± 5.4 (13.2 - 28.1) | 26.0 ± 4.6 (21.2 - 35.1) |
| **Trail Making Test B, seconds** | 36.7 ± 6.3 (30.5 - 49.4) | 38.3 ± 7.4 (32.9 - 52.3) |

*Date are mean ± SD (range)

### 4.3.2 Protocol

Participants were required to walk at a self-selected pace along an 8.5 m long wooden walkway (which was ~1.5 m wide and elevated ~0.1 m) while wearing a full-body safety harness attached to a friction-less trolley (via a dynamic rock-climbing rope) mounted to an I-beam along the ceiling of the laboratory. The middle portion consisted of six different types of ground terrain (2 solid, 3 compliant, 3 rocky, 3 irregular, 3 tilt, and 1 slippery), each 0.5 m x 0.5 m, and formed a 5 x 3 grid of 15 surfaces (i.e. multi-surface terrain section) (see Fig. 4.1). The compliant surfaces were covered with a thin green fabric to simulate wet, soggy, grass and were composed of medium-density foam (stiffness ~13 kN/m; maximum compression of ~0.08 m). The rocky surfaces were composed of a bed of small irregularly shaped rocks ranging in size from 1x1.5 cm to 2x5 cm. The irregular surfaces had irregularly spaced custom-made rock-climbing holds mounted on the top with a height ranging from 1 to 3 cm and spacing between holds ranging from 2 to 5 cm. The tilt surfaces were constructed with a 10º downward tilt (either to the left or right in the frontal plane) and are referred to as Tilt – L or R. Finally, the slippery surface was made of a piece of white ultra-high molecular weight polyethylene (used for artificial ice in rinks) mounted on a wooden base.

Prior to data collection participants tested each surface by stepping on them so that they could experience the stability and characteristics of the surfaces. Subsequently, participants performed four walking trials where the entire walkway consisted of a uniform solid surface (i.e. control walking). There were three different multi-surface terrain configurations in which participants had to walk across in the ensuing walking trials. The three configurations were constructed based on two factors: (1) the rocky, compliant, and irregular surfaces were always grouped with their other two respective surfaces (see Fig. 1) and (2) there were 2 solid, 1 slippery, 3 compliant, 3 rocky, 3 irregular and 3 tilt surfaces available (chosen to represent commonly encountered ground terrain and fit the size of the experimental set-up and laboratory space available) for each configuration. Following a ‘go’ signal, a board obstructing the participant’s view of the multi-surface terrain configuration was removed and they began to walk such that they took around four steps before reaching the multi-surface terrain section (approximately 3 – 4 seconds). There were four walking conditions: (1) natural (no path restrictions in that participants were free to choose which surfaces to step on), (2) start left (start walking across the multi-surface terrain section at the leftmost column), (3) start center (start walking across the multi-surface terrain section in the middle column), and (4) start right (start walking across the multi-surface terrain section at the rightmost column). Two vertical posts were positioned on either side of the appropriate surface of the first row of the multi-surface terrain configuration to denote the restricted path condition and participants were required to walk through them. Once past the posts, participants were free to choose which surfaces to step upon. However, participants were instructed to walk to an end goal marked with an 'x' on a piece of white paper mounted on the end of the walkway and visible throughout the trial. The four conditions were randomly presented within each configuration. Each block of trials of a particular configuration was repeated two times in random order for the older adults (and three times of for the young adults). Only the first trial of each configuration and condition combination (i.e. a total of 12 trials per participant) was used in the analysis so that each potential path was somewhat novel and any influence from learning was avoided.

Gaze fixations were recorded with an Applied Science Laboratories (ASL, Bedford, MA, USA) model 501 eye tracker mounted on the participant's head (weight under 227 g). This system has a precision better than 0.5º and spatial error less than 2º. Both pupil and corneal reflections from the left eye were captured to provide the line of sight (or fixation point) which was superimposed as a black square on the video image of the scene camera (mounted on the eye tracker on the person's head, which provides a view of what the individual 'sees'). A room camera (Panasonic Canada, Mississauga, Ontario, Canada) was positioned to capture a saggital view of the multi-surface terrain configuration. Video information of the eye, scene, and room camera were combined (see Fig. 1) using two digital mixers and recorded to DVD at 30 Hz. The eye tracker was calibrated for each participant using a nine-point calibration procedure which required the person to fixate a series of nine points in a rectangular grid on the floor in front of them and was re-checked periodically throughout the testing procedure.

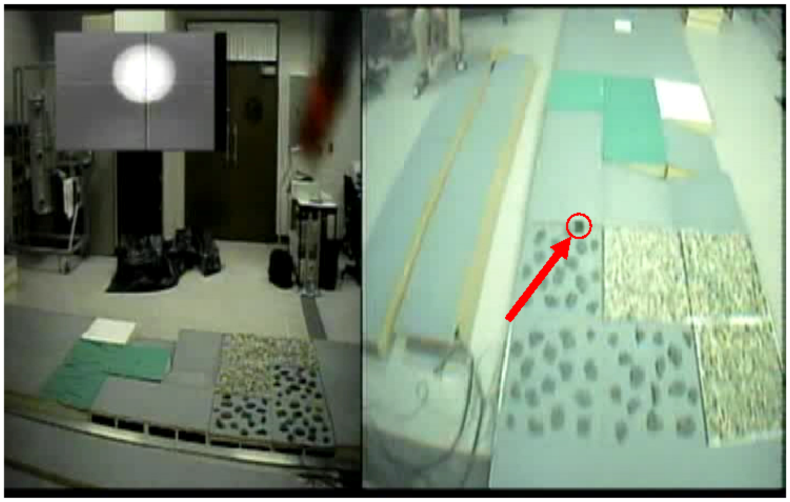


**Figure 4.1:** An example of one of the multi-surface terrain configurations and a gaze fixation to a transition region (denoted by the arrow and circle around the black cursor, which is superimposed on the video image). The left panel of the split screen image is from a saggital camera showing the terrain and the right panel is from the 'scene' camera mounted on the participant's head.

### 4.3.3 Data and statistical analysis

Frame-by-frame analysis of the combined video data was completed for each participant to identify gaze fixations throughout the trials (Marigold and Patla 2007; Patla and Vickers, 1997, 2003). A fixation was defined as gaze stabilized on a location for three consecutive frames (~100 ms) or longer (Marigold and Patla 2007; Patla and Vickers, 1997, 2003). Fixations to the following locations were identified: solid, slippery, irregular, rock, compliant, and tilt surfaces, transition region between two different surfaces (transition-2), transition region between three/four different surfaces (transition-3/4), end goal, areas before (pre) and after (post) the multi-surface terrain section, and all other locations (other). The determination of the location of fixation (to a surface and/or transition region) was based on visual identification of the position of the black cursor; the accuracy was periodically checked by another person blinded to the study. A fixation was directed to a transition region if the cursor was directly on the transition point or on either side of it but within a space equivalent to the size (see Fig. 4.1) of the black cursor.

Our data are divided into an approach phase, consisting of the time from the start of the trial to the first step on the multi-surface terrain section and a multi-surface phase, consisting of the first step on the multi-surface terrain section until stepping off the last surface (as determined from the video data).

A task-relevant fixation was a fixation directed to a surface location or transition region that was eventually stepped on (i.e. the participant stepped on the surface panel within which the fixation was located) while crossing the multi-surface terrain section (Marigold and Patla 2007). A three-way ANOVA with condition (natural vs. restricted) and location (area stepped on vs. area not stepped on) as the within-subject factors and age (young vs. older) as the between-subject factor for both the approach and multi-surface phases was performed.

To address specific influences of aging on fixation patterns we compared young and older adults on (1) fixation durations and (2) percent fixations directed to different rows of the multi-surface terrain section. The mean duration of each fixation was determined along with the total fixation time (i.e. all fixation durations pooled) and compared between the young and older adult groups with independent t-tests. We hypothesized that older adults would shown longer fixation durations and total fixation time.

We hypothesized that older adults would fixate equally to all rows of the multi-surface terrain to essentially scan the entire layout and allow pre-planning of a path. This strategy would enable the older adults to be better prepared for upcoming ground terrain challenges as opposed to a more on-line strategy of having only one or two steps to adjust as is seen in young adults. Thus, the percent of fixations directed to the first two rows of the multi-surface terrain (including all transition regions) was calculated and compared to the percent of fixations directed to the last two rows of the multi-surface terrain section (including all transition regions) for the approach phase. A two-way ANOVA with cluster (first two rows vs. last two rows) as the within-subject factor and age (young vs. older) as the between-subject factor was performed. As over 90 % of fixations were directed to the last two rows during the multi-surface phase for both age groups no statistics were performed for this phase.

Fixations among the three restricted path conditions (i.e. start left, center, and right) within a particular multi-surface terrain configuration were pooled. Subsequently the fixations for these conditions along with the natural condition (i.e. free to choose path) were normalized to correct for the different probability (i.e. different number of possible fixation locations due to different number of surface types and transition regions) of fixating on a particular surface or transition region (Marigold and Patla 2007). Normalization was accomplished by dividing the number of fixations to each surface or transition region by the number of possible surface locations or transition regions of the same type available to fixate within a particular configuration. Fixations across the different configurations were then pooled to determine a normalized mean number of fixations to a particular location.

We compared the normalized mean number of fixations directed to surfaces (all surfaces combined) versus transition regions (transition-2 and transition-3/4 locations) with a three-way ANOVA with condition (natural vs. restricted) and location (surface total vs. transition total) as the within-subject factors and age (young vs. older) as the between-subject factor for both the approach and multi-surface phases. Fixations to transition-2 and transition-3/4 regions were then compared using a three-way ANOVA with condition (natural vs. restricted) and location (transition-2 vs. transition-3/4) as within-subject factors and age (young vs. older) as the between-subject factor for both the approach and multi-surface phases. Finally, we compared fixations among the six different surfaces using a three-way ANOVA with condition (natural vs. restricted) and location (solid, slippery, irregular, rocks, tilt, and compliant) as the within-subject factors and age (young vs. older) as the between-subject factor for both the approach and multi-surface phases.

Finally, we performed a two-way ANOVA comparing the percent of fixations directed to the multi-surface terrain or control equivalent between the age groups such that condition (control and multi-surface) and age (young and older) were the factors. We also performed a two-way ANOVA comparing the frequency of fixations among the young and older adults between the control and multi-surface terrain conditions.

An alpha level of 0.05 was chosen for significance for all statistical analyses. The data were rank or arcsine transformed where appropriate if the data was not normally distributed (as determined by examination of normality plots and the Shapiro-Wilk test).

## 4.4 Results

The mean number of fixations made during the control walking and multi-surface walking trials were 11.5 ± 2.2 and 18.3 ± 3.3, respectively, for the young adults. Older adults demonstrated a mean number of fixations during the control walking and multi-surface walking of 15.2 ± 1.5 and 18.8 ± 2.1, respectively. The frequency of fixations during the control walking condition was significantly greater in the older adults compared to the young adults as evident from post hoc analysis of the Condition X Age interaction ($F_{1,9}$ = 9.20, P = 0.014). During the multi-surface walking trials 91.1 ± 10.3 % of fixations were directed to the multi-surface terrain compared to only 55.8 ± 22.7 % of fixations directed to the equivalent location (i.e. the uniform solid surface where the different surfaces were present in the multi-surface walking trials) for the control walking trials of young adults. In contrast, 94.4 ± 4.3 % of fixations were directed to the multi-surface terrain and 74.0 ± 19.3 % of fixations were directed to the equivalent location for the control walking trials of the older adults. However, there was only a Condition main effect ($F_{1,9}$ = 44.53, P < 0.0001) showing that the percent of fixations directed to the multi-surface terrain or control equivalent was greatest when the different ground terrain were present.

The older adults demonstrated that ~54 % of fixations were directed two steps ahead (~1.2 ± 0.11 seconds) while negotiating the multi-surface terrain (determined from the step preceding the multi-surface terrain and two steps after). In terms of where people actually stepped when traversing the multi-surface terrain section, 21.6 % of steps were on the rock surfaces compared to 20.2 % on the irregular surfaces, 18.7 % on the solid surfaces, 13.8 % on the compliant surfaces, 11.5 % on the transition region between two different surfaces, 9.5 % on the tilt surfaces, 3.7 % on the slippery surface, and 0.9 % on the transition region between four different surfaces. Thus, approximately 88 % of steps were onto actual surfaces whereas only 12 % of steps were made onto a transition region.

Gaze fixation patterns showed that fixations were directed to task-relevant locations during both the approach (Fig. 4.2a) and multi-surface (Fig. 4.3a) phases regardless of age. Fixations were heavily favored to areas (i.e. surface blocks or transition regions) that would eventually be stepped on during both the approach (ANOVA location main effect: $F_{1,12}$ = 93.56, P < 0.0001) and multi-surface phases (ANOVA location main effect: $F_{1,12}$ = 65.69, P

< 0.0001). In fact, fixation patterns were largely influenced by the task instructions as seen for young adults (Marigold and Patla 2007). In the natural condition older adults showed 25.5 ± 8.4 %, 65.1 ± 8.5 %, 9.4 ± 11.2 % of fixations were directed to the left, center, and right columns, respectively. Fixations were relatively spread out in this condition compared to the restricted conditions for the older adults. In particular, in the start left condition, 86.1 ± 17.0 % of fixations were directed to the left column versus only 13.9 ± 17.0 % fixations to other columns. In the start centre condition, 93.1 ± 6.1 % of fixations were directed to the center column compared to 6.9 ± 6.1 % of fixations to other columns. In the start right condition, 87.5 ± 14.6 % of fixations were directed to the right column and 12.5 ± 14.6 % of fixations were directed to the other columns.

We hypothesized that older adults would fixate longer on features of the environment during this complex walking task and that this would be due to their slower cognitive processing ability and/or poor visual function. However, there were no differences in fixation duration (t-test, P = 0.652) or total fixation time (t-test, P = 0.889) between the young (mean fixation duration = 257.6 ± 43.2 ms; mean total fixation time = 24.6 ± 9.6 seconds) and older adults (mean fixation duration = 265.3 ± 45.2 ms; mean total fixation time = 25.1 ± 10.1 seconds).

Additionally, we were interested in whether older adults directed gaze fixations to the entire layout (i.e. fixations spread out equally to the front and back rows of the multi-surface terrain section) of the upcoming environment to facilitate path planning ahead of time or whether fixations were directed to specific sections of the terrain as they walked similar to young adults. Although there were no differences between the young and older adults (P > 0.05), there was a significant main effect for cluster (ANOVA cluster main effect: $F_{1,12} = 26.01$, P = 0003) showing a greater percentage of fixations directed to the first two rows compared to the last two rows during the approach phase. Specifically, 63.2 ± 14.3 % and 68.4 ± 21.6 % of fixations for the young and older adults, respectively, were directed to the first two rows during the approach phase. In contrast, only 21.8 ± 14.9 % of fixations for the young adults and 19.2 ± 19.2 % of fixations for the older adults were directed to the last two rows of the multi-surface terrain during the approach phase.

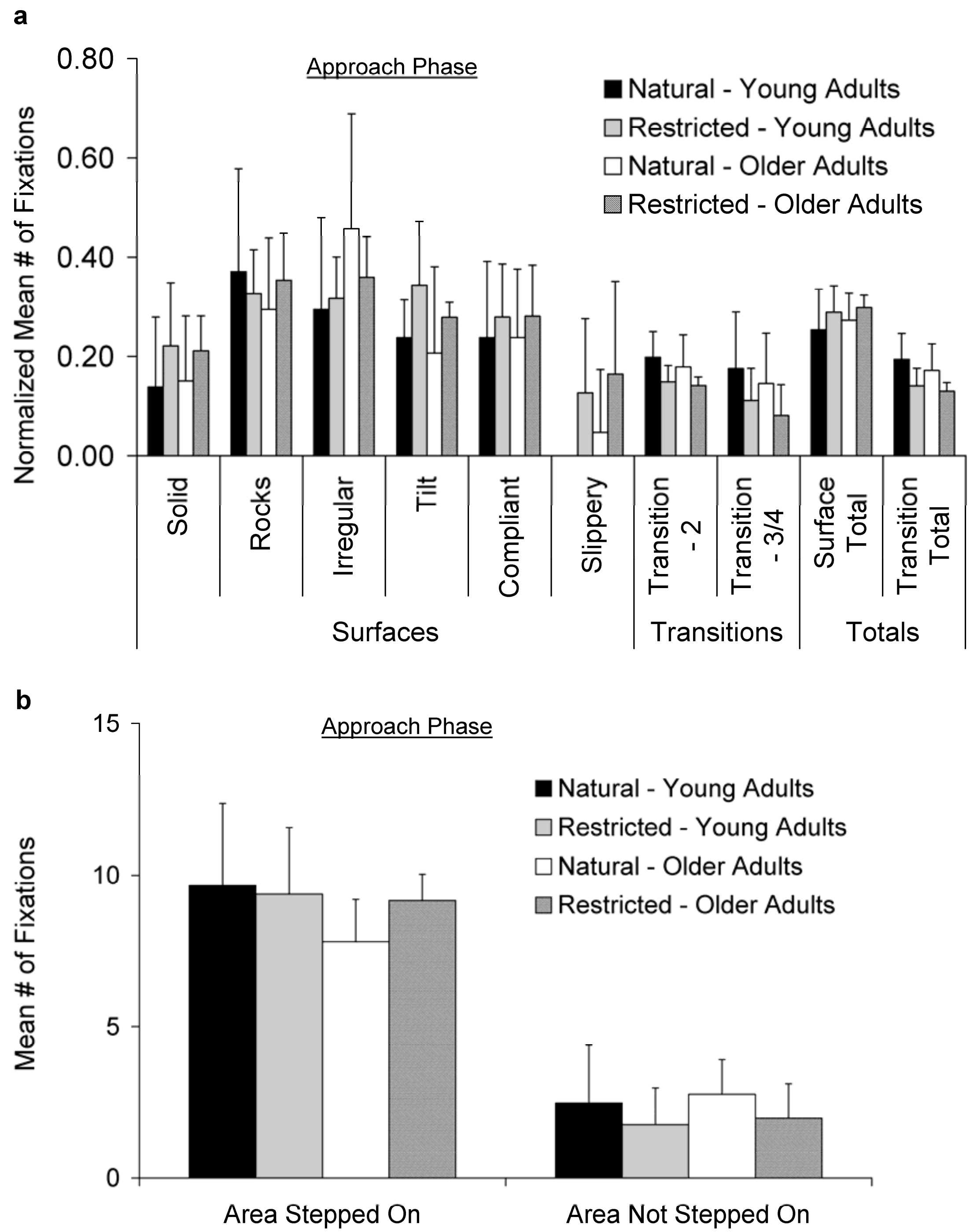



**Figure 4.2:** Gaze fixation patterns during the approach phase for the young (N = 7) and older (N = 7) adults. (a) Normalized mean number of fixations directed to a particular surface or transition region. Normalization involved dividing the number of fixations by

the number of available locations for each surface and transition type before calculating the mean number of fixations. Also illustrated (b) are task-relevant fixations. For the task-relevant fixations the mean number of fixations directed to an area (i.e. surface or transition region) that was eventually stepped on compared to an area that was not stepped on is shown. Error bars represent standard deviation.

During the approach phase (see Fig. 4.2b), when we compared fixations directed to surfaces (all surfaces pooled) with fixations directed to transition regions (transition-2 and transition-3/4 pooled) we found no Age effects ($P > 0.05$). However, there was a significant Location main effect (ANOVA: $F_{1,12} = 90.11$, $P < 0.0001$) showing a greater number of fixations to surfaces compared to transition regions and a Condition X Location interaction (ANOVA: $F_{1,12} = 14.58$, $P = 0.002$). When we examined fixations to the different types of surfaces independently, we found a Condition (ANOVA: $F_{1,12} = 18.38$, $P = 0.001$) and Location main effect (ANOVA: $F_{5,60} = 10.16$, $P < 0.0001$) demonstrating a greater number of fixations in the restricted path condition versus the natural path condition and fixations were more common to the irregular, rock, compliant, and tilt surfaces compared to the solid and slippery surfaces. However, there were no Age effects ($P > 0.05$). When comparing fixations to transition-2 versus transition-3/4 regions only a significant Condition main effect (ANOVA: $F_{1,12} = 8.59$, $P = 0.013$) was seen demonstrating a greater number of fixations in the natural compared to restricted path conditions.

During the multi-surface phase (see Fig. 4.3b), when we compared fixations directed to surfaces (all surfaces pooled) with fixations directed to transition regions (transition-2 and transition-3/4 pooled) we also found no Age effects ($P > 0.05$). However, there was a significant Location main effect (ANOVA: $F_{1,12} = 33.67$, $P < 0.0001$) showing a greater number of fixations to surfaces compared to transition regions. When comparing fixations to the different types of surfaces independently, we found significant Age X Condition interaction (ANOVA: $F_{1,12} = 7.86$, $P = 0.016$) where LS means post-hoc testing demonstrated a greater number of fixations in the older adults for the restricted path condition compared to the other conditions and young adults. In addition, we found a significant Condition X Location interaction (ANOVA: $F_{5,60} = 9.93$, $P < 0.0001$).

Furthermore, we found a significant Location main effect (ANOVA: $F_{5,60} = 9.63$, $P < 0.0001$). Duncan's post-hoc testing demonstrated the greatest number of fixations to the

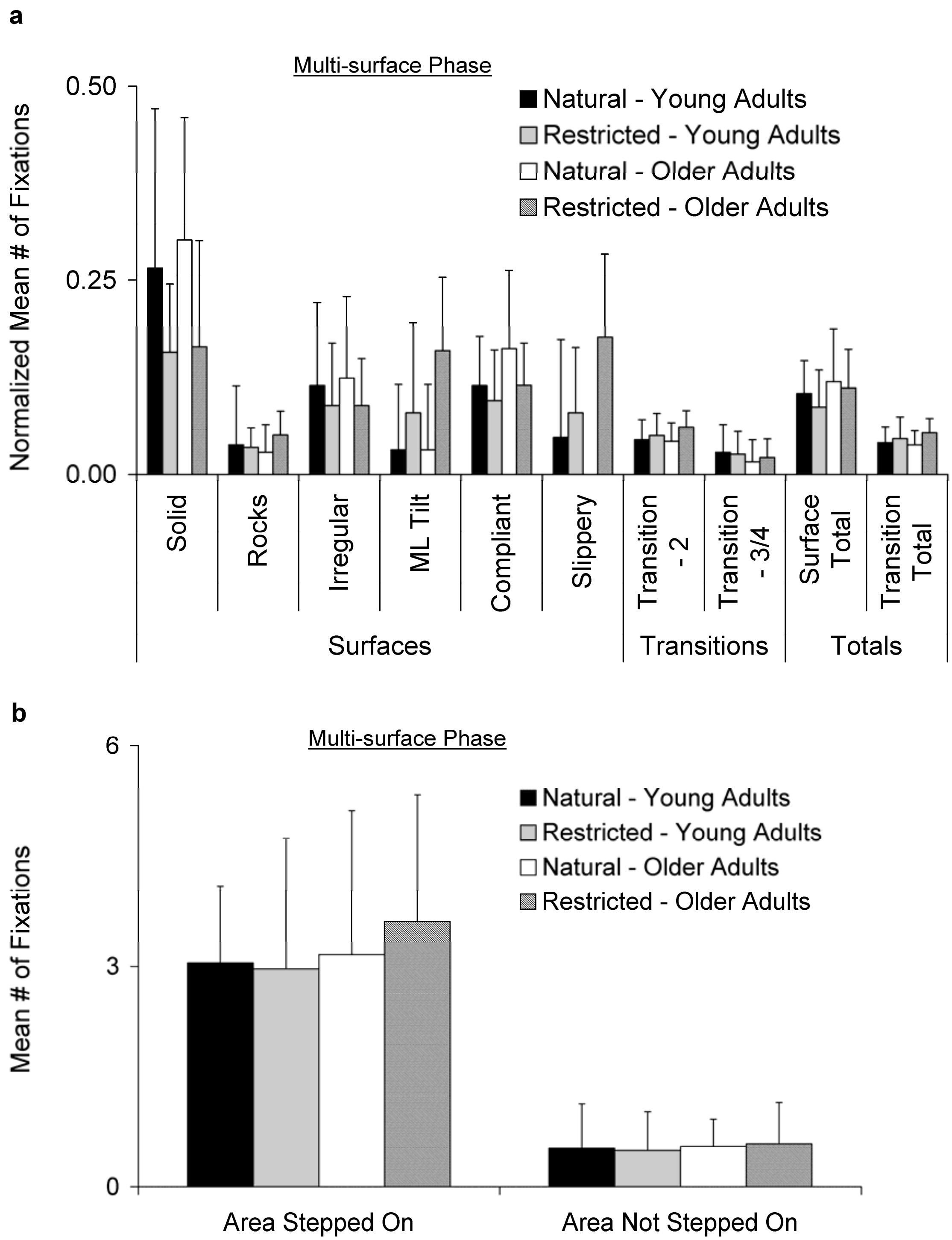


**Figure 4.3:** Gaze fixation patterns during the multi-surface phase for the young (N = 7) and older (N = 7) adults. (a) Normalized mean number of fixations directed to a particular surface or transition region. Normalization involved dividing the number of fixations by the number of available locations for each surface and transition type before calculating the mean number of fixations. Also illustrated (b) are task-relevant fixations. For the task-relevant fixations the mean number of fixations directed to an area (i.e. surface or transition region) that was eventually stepped on compared to an area that was not stepped on is shown. Error bars represent standard deviation.

solid surfaces. When comparing fixations to transition-2 versus transition-3/4 regions only a significant Location main effect (ANOVA: $F_{1,12} = 16.27$, $P = 0.002$) was seen demonstrating a greater number of fixations to transition-2 regions compared to transition-3/4 regions.

## 4.5 Discussion

We sought to determine whether age affects gaze fixation patterns while walking on varying ground terrain. Surprisingly, gaze fixation patterns among the older adults were nearly identical to the young adults. The results demonstrated that older adults fixate on task-relevant areas (i.e. future stepping locations) appropriate for the task instructions (i.e. fixations clustered along the column to walk in the restricted path conditions). Thus, fixating task-relevant areas appears to be a common strategy among age groups and different tasks (Ballard et al. 1992; Geruschat et al. 2003; Land and Hayhoe, 2001; Land et al. 1999; Pelz and Canosa, 2001). Furthermore, older adults frequently fixated a transition region between two different surfaces. This efficient strategy may serve to increase the amount of information gathered by covertly attending to both surfaces.

While Hollands et al. (1995) have shown that individuals make a horizontal saccade onto a subsequent step target just prior to every step, which also may be expected as the terrain becomes more difficult, we found older and younger (Marigold and Patla 2007) adults fixate predominantly two steps ahead (~1.2 seconds) while traversing the multi-surface terrain. This is similar to the findings of Patla and Vickers (2003) for stepping onto targets. Avoidance strategies and direction changes can be implemented if visual information is obtained at least two steps ahead (Patla 1997). Thus, it may not be necessary to direct fixations to the subsequent step or to the entire multi-surface terrain while approaching it. Both young and older adults fixate predominantly to the first two rows (63 % and 68 %, respectively). Thus, rather than fixating each of the 15 surface blocks and fixating equally to all rows of the multi-surface terrain, both young and older adults fixate small sections of the terrain and fixate additional rows as they approach them. This suggests that the route is planned on-line. Older adults at a high-risk of falling may choose to scan the entire layout of the multi-surface terrain in order to pre-plan the safest and most efficient route rather than relying on the ability to rapidly change direction or having to step over an obstacle (such as created by the tilt surface). However, this does not necessarily mean that young and older adults are not attending (using peripheral vision from the lower visual field) to a closer location (or subsequent step) on the multi-surface terrain. Indeed, peripheral vision of an approaching obstacle in the travel path is sufficient for successful obstacle avoidance: re-direction of gaze is not essential (Marigold et al. 2007).

Previous studies of young and older adults stepping over obstacles and onto targets in the travel path have shown that older adults initiate a downward saccade earlier to the obstacle or target and fixate longer (Chapman and Hollands 2005; Di Fabio et al. 2003a,b). We failed to show differences in fixation duration or total fixation time in the present study. This may be due to the nature of our task. First, as the multi-surface terrain is quite rich with visual information it may be more essential to fixate many different areas rather than spending a greater amount of time on any one particular location. Second, since re-fixations (i.e. fixations to a previously fixated region) were possible (and observed for both the young and older adults) this strategy may serve to provide additional visual processing time of a certain feature of the travel path. Finally, in the previous studies there was a greater spatial constraint on where the older adults were required to step. Fixation durations may have been longer in order to ensure precise foot placement. In the present study there were only minor limitations on where the participants were allowed to step.

While visual function was attenuated in the older adults compared to the young adults our sample of older adults consisted of generally healthy individuals. Furthermore, our older adult sample was relatively young: the mean age was only 65 years. Thus, it is possible that these factors contributed to the findings of similar fixation patterns between the age groups. These factors may also explain why fixation durations were not different between the young and older adults as has been found in previous studies (Chapman and Hollands 2005; Di Fabio et al. 2003a,b). More high-risk older adults and those over 70 years of age may show different results. Interestingly, in a sample of two older adults wearing multi-focal lenses gaze fixation patterns were different than older adults not wearing multi-focal lenses and young adults: fixations were directed nearly equally to the first two and last two rows of the multi-surface terrain while approaching it (Marigold and Patla, unpublished observations). This strategy may be the result of the inability to clearly see at a distance out of the lower portion of these lenses. However, further study with individuals with multi-focal lenses is warranted before any conclusions can be drawn. In fact, it would be beneficial for future studies to address older adults with a range of conditions and across different age groups.

Nonetheless, it is encouraging that healthy older adults show similar gaze patterns to their young counterparts. Acquiring appropriate visual information from the environment, particularly when the ground terrain poses a threat to balance, is imperative in order to guide safe foot placement and prepare for changing surface characteristics. That gaze fixation patterns among the older adults are similar to young adults does not imply stability is not affected. Rather, it is more likely that balance is compromised in the older adults. For example, step width variability is increased in older women while walking on irregular terrain (Thies et al. 2005a). In addition, processing of the sampled visual information may be poorer among the older adults and the quality of the visual information may be deficient due to declines in contrast sensitivity and acuity.

Interestingly, both the young and older adults stepped predominantly on the rock, solid, and irregular surfaces. These first two surfaces are probably the most commonly encountered in everyday life while walking outdoors. Thus, there may have been a certain level of comfort for stepping on these surfaces. In addition, these three surfaces were most likely the least threatening in terms of stability (see Chapter 2) and therefore the choice to use these surfaces was highly appropriate.

In conclusion, age does not influence gaze fixation patterns while walking across varying ground terrain. Gaze fixations of healthy older adults while negotiating complex ground terrain are directed in a highly task-relevant manner to specific features of the environment to help guide foot placement.

### 4.6 Bridging summary

While the two experiments on gaze fixation patterns as individuals negotiated the multi-surface terrain provide valuable information regarding the role of visual information for this task the other aspect of this thesis that needs to be addressed is the notion of how stability is influenced when walking on these challenging surfaces. In particular, we were interested in how aging affects stability to better understand why these individuals are more likely to fall. There has been no research to date on how individuals of any age walk on multiple types of unstable ground terrain in the same travel path despite the frequency with which this occurs in everyday life. Thus, the following experiment attempts to address this question.

## CHAPTER 5 – Consequences of age on stability while walking across varying ground terrain

### 5.1 Abstract

Different types of ground terrain are frequently encountered during walking in the environment. Given the known sensorimotor deficits and high frequency of falls among older adults it is surprising little research has been done to understand how individuals walk and control balance in these situations. Thus, the purpose of this study was to determine the effects of aging on stability while walking on varying, unstable, ground terrain. Ten healthy young and ten healthy older adults walked along a walkway where the middle portion consisted of different types of ground terrain while kinematic measures were recorded. Measures of stability included trunk pitch and roll root-mean-square (RMS) deviation, anterior-posterior (AP) and medial-lateral (ML) trunk centre of mass (COM) acceleration RMS, and AP, vertical, and ML head acceleration RMS. In addition, step parameters of gait speed, step length, and step width were determined. Trunk pitch and roll RMS were greater among the older adults compared to the young adults. In addition, older adults adopted a cautious gait strategy consisting of slower gait speed and a shorter step length, which actually led to attenuated trunk AP COM acceleration and head acceleration RMS. The results suggest that older adults are more unstable when traversing varying, unstable, ground terrain, particularly in the ML direction. Given the risk of hip fracture from falls to the side among older adults, further research on understanding how the nervous system controls balance when walking in challenging situations such as this is warranted.

## 5.2 Introduction

Changes in ground terrain which compromise stability must be overcome in order to maintain balance while walking. We often encounter several different types of ground terrain in our travel path that we may or may not be able to avoid. These situations may be particularly challenging for older adults due to deterioration of visual function and muscle strength in addition to sensory deficits. Not surprisingly, fall risk is increased among older adults (Berg et al. 1997; Blake et al. 1988; Tinetti et al. 1988). Furthermore, a large proportion of falls in older adults occur while walking (Berg et al. 1997; Norton et al. 1997).

Albeit limited, we have begun to understand how individuals anticipate, recover, and maintain balance following stepping on an unstable surface. A common feature of the recovery responses to these unstable surfaces and other perturbations evoked during walking is that the nervous system coordinates the whole body to maintain balance (Marigold and Patla 2005; Marigold et al. 2003; Misiaszek 2003). Stepping on an unexpected slippery (Marigold and Patla 2002), compliant (Marigold and Patla 2005) or inverting (Nieuwenhuijzen et al. 2002) surface elicits rapid reflex responses in the arms and legs in young adults. Individuals adjust to accommodate slippery terrain by an anterior shift of their centre of mass resulting from a decreased step length and by reducing their braking impulse: these changes among others facilitate the reduction in perturbation magnitude and prevent a loss of balance (Bhatt et al. 2006a). Unfortunately, information on recovery responses of older adults following stepping on unstable surfaces is lacking considerably. However, Tang and Woollacott (1998, 1999) have shown that with age, postural reflexes exhibit longer onset latencies, reduced magnitude, and longer burst durations following a slip during walking.

Although knowledge of the upcoming perturbation and experience with the surface characteristics can dramatically reduce the magnitude of a destabilizing event and even eliminate the need for a recovery response (Bhatt et al. 2006a; Cham and Redfern 2002; Marigold and Patla 2002, 2005), how the nervous system deals with continued perturbations caused by multiple and different unstable ground terrain is not known. In a step towards understanding this balance control challenge, stability during multiple steps on a single type of unstable surface has been examined. MacLellan and Patla (2006a) have recently investigated walking across compliant terrain in young adults, who display increases in toe clearance after each step along with increased step length and width compared to walking on solid level ground. Interestingly, frontal plane stability does not seem to be influenced when walking on the compliant terrain as evident from no differences in medial-lateral (ML) centre of mass (COM) and trunk movements; rather the nervous system tightly modulates stability in this direction (MacLellan and Patla 2006a). On irregular terrain, older adults adopt a cautious walking strategy compared to younger adults as demonstrated by a reduced gait speed, decreased step length, and increased variability of step width and step timing (Menz et al. 2003a; Thies et al. 2005a).

However, there is currently no information as to how individuals of any age accommodate varying ground terrain as they traverse through more complex environments. Given that a large proportion of falls occur while walking in older adults and the known changes in sensorimotor function with aging, it is important to fully understand how stability is compromised when negotiating unstable ground terrain. Thus, the purpose of this study was to determine the effects of aging on stability while walking on varying, unstable, ground terrain. Since the majority of the body's mass comes from the trunk and head regions and is situated substantially above ground level creating an inherently unstable system (Winter 1991), we chose to examine trunk and head motion as a means of assessing stability while walking across varying ground terrain.

## 5.3 Methods

### 5.3.1 Participants

Ten healthy young adults (5 female, 5 male; mean ± SD age = 26.1 ± 5.2 yrs.) and ten healthy older adults (5 female, 5 male; mean ± SD age = 74.1 ± 7.2 yrs.) volunteered for this study. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behaviour in this study. Participants wore corrective lenses if necessary: no participants wore multi-focal lenses. Visual testing consisting of binocular visual acuity and binocular contrast sensitivity were performed using a Bailey-Lovie type logMAR chart read at 6.3 meters (and thus providing a range of 0.8 to -0.5 log MAR) and a Pelli-Robson contrast sensitivity chart read at 1 meter, respectively. A self-reported 6-month retrospective fall history was also determined. Balance confidence, functional mobility, and visuomotor processing ability were assessed using the Activities-specific balance confidence (ABC) scale (Powell and Myers 1995), timed up and go test (Podsiadlo and Richardson 1991), and the Trail Making Test (part A and B) (Tombaugh 2004), respectively, to provide an overall picture of the abilities of the young and older adults (see Table 5.1).

The study was approved by the Office of Research Ethics at the University of Waterloo and informed written consent was received from all participants.

**Table 5.1:** Participant characteristics.

| Characteristics* | Young Adults (N = 10) | Older Adults (N = 10) |
|---|---|---|
| **Age, years** | 26.1 ± 5.2 (20 - 37) | 74.1 ± 7.2 (61 - 82) |
| **Gender, Male/Female** | 5/5 | 5/5 |
| **Timed Up and Go, seconds** | NA | 9.7 ± 1.9 (8.0 - 13.6) |
| **ABC scale, %** | 96.4 ± 3.5 (88.1 - 100) | 93.4 ± 7.1 (81.9 - 100) |
| **Trail Making Test A, seconds** | 16.3 ± 2.5 (12.9 - 19.3) | 31.0 ± 10.7 (20.8 - 51.4) |
| **Trail Making Test B, seconds** | 35.6 ± 14.6 (24.4 - 75.1) | 65.6 ± 28.1 (44.0 - 138.4) |
| **# of Fallers** | 2 | 1 |

*Date are mean ± SD (range)

NA = not available

### 5.3.2 Protocol

Participants were required to walk at a self-selected pace along a painted (medium shade of grey) wooden walkway (~8.5 m long, ~1.5 m wide and elevated ~0.1 m) where six different types of ground terrain (2 solid, 3 compliant, 3 rocky, 3 irregular, 3 tilt, and 1 slippery), each 0.5 m x 0.5 m, formed a 5 x 3 grid of 15 surfaces (i.e. multi-surface terrain section) in the middle portion (~2.5 m long) (see Appendix A). The solid, tilt, and irregular surfaces were painted the same color as the walkway. The solid surfaces were constructed the same as the rest of the walkway and posed no challenge. The irregular surfaces had irregularly spaced custom-made dark grey rock-climbing holds mounted on the top. The height of these rock-climbing holds ranged from 1 to 3 cm and the spacing between holds ranged from 2 to 5 cm. The compliant surfaces were composed of medium-density foam (stiffness ~13 kN/m; maximum compression of ~0.08 m) and covered with a thin green fabric (to simulate wet, soggy, grass). The rocky surfaces were composed of a bed of small irregularly shaped rocks (ranging in size from 1 x 1.5 cm to 2 x 5 cm). The tilt (or uneven) surfaces were constructed such that they had a 10º downward tilt (either to the left or right in the frontal plane) and are referred to as Tilt – L or R. The slippery surface was made of a piece of white ultra-high molecular weight polyethylene (used for artificial ice in rinks) mounted on a wooden base. Each participant wore a full-body safety harness attached to a friction-less trolley (via a dynamic rock-climbing rope) mounted to an I-beam along the ceiling of the lab.

Participants performed four walking trials at the start of the experiment where the entire walkway consisted of a uniform solid surface (i.e. control walking) and walked to an end goal. There were three different multi-surface terrain configurations in which participants had to walk across in subsequent walking trials for the young adults and only two different configurations for the older adults. There were fewer configurations for the older adults to reduce the number of walking trials due to fatigue and time constraints. The two/three configurations were randomly constructed based on two factors: (1) there were 2 solid, 1 slippery, 3 compliant, 3 rocky, 3 irregular and 3 tilt surfaces available (chosen to represent commonly encountered ground terrain and fit the size of the experimental set-up and laboratory space available) for each configuration and (2) the rocky, compliant, and irregular surfaces were always grouped with their other two respective surfaces (see Fig. 5.1 and Appendix A). A board obstructed the participant's view of the multi-surface terrain configuration prior to the start of each trial. Following a 'go' signal, the board obstructing the participant's view was removed and they began to walk such that they took around four

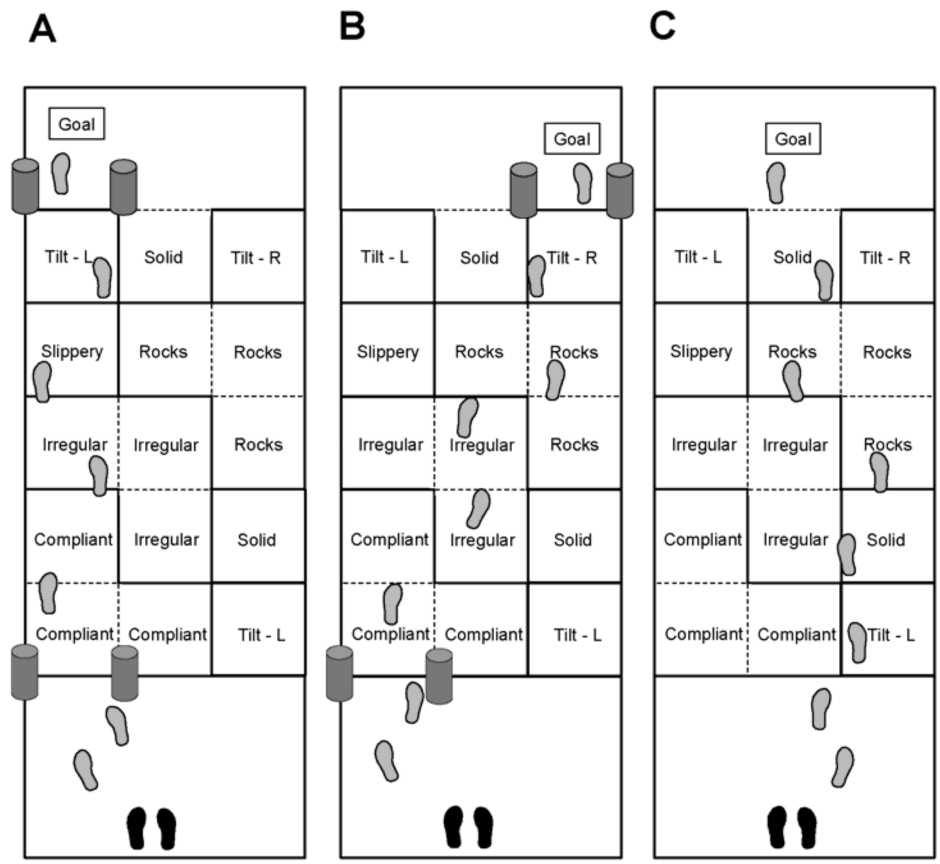



**Figure 5.1:** Experimental set-up and protocol for the multi-surface terrain configurations. (A) Column condition where the gates are set at the beginning and end of the left (as shown), centre, or right column of the multi-surface terrain section. (B) Cross condition where the gates are set at the beginning and end of different columns (start left – end right condition shown). (C) Natural condition where there were no gates present and participants could step on any surface.

steps before reaching the multi-surface terrain section (approximately 3 – 4 seconds). The path to walk across the multi-surface terrain was manipulated such that there were three conditions (see Fig. 5.1): column, cross, and natural. In the natural condition, participants were free to choose which surfaces to step on. In the other two conditions, two sets of two vertical posts were positioned on either side the appropriate surface of the first and last row of the multi-surface terrain configuration and participants were required to walk through them. Between the posts participants were free to choose which surfaces to step on. In the column conditions, the vertical posts were positioned along the left, centre, or right column of the multi-surface terrain. In the cross conditions, participants had to cross over one or two columns of the multi-surface terrain such that there were the following combinations within this condition: start left/end centre, start left/end right, start centre/end left, start centre/end right, start right/end centre, start right/end left. However, regardless of the conditions, participants were instructed to walk to an end goal marked with an 'x' on a piece of white paper mounted on the end of the walkway and visible throughout the trial. The three conditions were randomly presented within each multi-surface terrain configuration. Each block of trials of a particular configuration was presented once in random order (see Appendix F).

Three Optotrak cameras were used to collect kinematic data (sampling frequency of 60 Hz) and a video camera recorded the walking trials from the left side of the participant's body for qualitative observations. Position markers (infrared emitting diodes) were placed bilaterally on the ankles, iliac crests, and sternal end of the clavicles, as well as on the xyphoid process, chin, and head. For the head, a plastic band was used that contained a cluster of five markers centered on the forehead and a marker off to the side (closer to the left ear). The cluster of markers was important as this way at least one marker was visible to the cameras regardless of where the participant moved their head. A custom-written program in MATLAB low-pass filtered the position data for all markers at 6 Hz (2$^{nd}$ order, dual-pass, Butterworth algorithm) and processed all kinematic data.

### 5.3.3 Coordinate frames

The coordinate frames which describe the motion of the body, trunk, and head while moving through space were defined in a hierarchical manner as described by Courtine and Schieppati (2003) and Imai et al. (2001). The primary coordinate frame was the spaced-fixed reference frame of the Optotrak system ($X_S$, $Y_S$, $Z_S$) of the body relative to space, the vertical axis ($Y_S$) of which was parallel to the direction of gravity (positive being upwards), the anterior-posterior (AP) axis ($X_S$) was parallel to the direction of straight walking (positive being forward) and orthogonal to the $Y_S$-axis, and the ML axis ($Z_S$) was positive to the participant's right and orthogonal to the $X_S$-$Y_S$ plane. While walking in this task the body follows a trajectory in the $X_S$-$Z_S$ plane, which can be determined by the linear motion of a point on the body ($x_s$, 0, $z_s$). To investigate the movements of the trunk and head in space a trajectory coordinate ($X_T$, $Y_T$, $Z_T$) frame was defined, the vertical axis ($Y_T$) of which was parallel to the vertical axis of the spatial coordinate frame ($Y_S$). Trunk COM was calculated from the iliac crest, xyphoid, and clavicle position markers using anthropometric data and segment definitions from Winter (2005). The linear velocity of the trunk COM in the $X_S$-$Z_S$ plane at each point of the trajectory determined the $X_T$-axis of the trajectory coordinate frame, which was in the direction of forward progression. This was defined as the heading direction whose rotation angle with respect to the spatial coordinate frame was calculated as follows (Courtine and Schieppati 2003):

$$\theta_T = Tan^{-1}\left(\frac{Z_T}{X_T}\right)$$

where the angle θ defines the heading of the trunk COM in space at any point on the trajectory. The heading angle was positive for a right turn. Subsequently, any vectors in the spatial coordinate frame could be converted to the trajectory coordinate frame through multiplication by the transformation matrix $R_T$ (Courtine and Schieppati 2003):

$$R_T = \begin{bmatrix} \cos\theta_T & 0 & \sin\theta_T \\ 0 & 1 & 0 \\ -\sin\theta_T & 0 & \cos\theta_T \end{bmatrix}$$

Trunk angles relative to the trajectory coordinate frame were calculated from the transformed trunk position markers. Trunk pitch was calculated as the angle between a vertical line (parallel to the $Y_T$-axis) and a line joining the bisection of the iliac crest markers and bisection of the clavicle markers parallel to the $X_T$-axis. Trunk roll was calculated as the angle between a vertical line (parallel to the $Y_T$-axis) and a line joining the bisection of the iliac crest markers and bisection of the clavicle markers parallel to the $Z_T$-axis. Thus, trunk pitch and roll movements were around the $Z_T$-axis and $X_T$-axis, respectively, where trunk pitch forward and trunk roll to the right were positive.

### 5.3.4 Data analysis

Foot contacts on the multi-surface terrain (or control walking trials equivalent) were determined based on the displacement profiles of the ankle markers using a computer algorithm combined with visual inspection. Subsequently, the mean step length and width (based on the displacement data of the ankle markers) were calculated. Gait speed across the multi-surface terrain (or control walking trials equivalent) was based on the displacement data of the xyphoid position marker.

The AP and ML trunk COM accelerations were determined by double differentiation of the AP and ML COM displacement data and AP, vertical, and ML head accelerations were determined by double differentiation of a single head position marker (from the cluster of markers on the head-piece). AP and ML stability margins (SM) based on the location of the trunk COM and ankle position markers (an estimate of the edge of the base of support) were also determined at each foot contact on the multi-surface terrain (or control condition equivalent). The AP-SM was calculated by subtracting the lead foot AP ankle marker position from the AP trunk COM position such that negative values indicated the trunk COM behind the lead foot with values approach zero representing the COM coming closer to the ankle marker of the lead foot. The ML-SM was calculated by subtracting the ML ankle marker position of the lead foot from the ML trunk COM position and corrected based on which foot was leading so that positive values indicated the ML trunk COM medial to the lead foot and values closer to zero indicating the trunk COM is closer to the ankle markers.

The trunk AP and ML COM accelerations, head accelerations, and trunk angles were determined from foot contact on the first surface of the multi-surface terrain until foot lift-off from the last surface of the multi-surface terrain. Subsequently, the root-mean-square (RMS) deviation (i.e. standard deviation) was calculated for each measure during this time interval and reflected trunk and head stability while walking on the multi-surface terrain.

### 5.3.5 Statistical analysis

The data were rank transformed, where appropriate, if the data were not normally distributed (as determined by examination of normality plots and the Kolmogorov-Smirnov test). An alpha level of 0.05 was chosen for significance for all statistical analyses.

A two-way ANOVA with Age (young and old) as a between-subject factor and Condition (control, column, cross, and natural) as a within-subject factor was performed for all measures. These measures included gait speed, mean step length and width, AP-SM, ML-SM, trunk AP and ML COM acceleration RMS, trunk pitch and roll RMS, and AP, vertical, and ML head acceleration RMS. Duncan's and LS-means post hoc tests were performed for the main effects and interactions, respectively, when significant.

## 5.4 Results

The young and older adults showed similar choices in terms of which surfaces to step on when walking across the multi-surface terrain. Young adults stepped a total of 25.3 % on the irregular surfaces, 21.5 % on the rocky surfaces, 19.2 % on the solid surfaces, 16.3 % on the compliant surfaces, 13.5 % on the tilt surfaces, and 4.2 % on the slippery surface. Older adults stepped a total of 23.9 % on the rocky surfaces, 22.9 % on the irregular surfaces, 21.3 % on the compliant surfaces, 13.1 % on the solid surfaces, 14.9 % on the tilt surfaces, and 3.9 % on the slippery surface. A more detailed description is shown in Table 5.2.

### 5.4.1 Step parameters and gait speed

The older adults adopted a cautious walking strategy reflected by a slower gait speed and shorter step length compared to the young adults (see Fig. 5.2). There was a significant Age X Condition interaction for gait speed ($F_{3,54} = 5.53$, $P = 0.002$), with post hoc analyses showing that for each condition (control, column, cross, and natural) the older adults walked slower than the young adults.

**Table 5.2:** Percentage of steps onto a particular surface of the multi-surface terrain.

| Condition | Age | Solid | Slippery | Rocks | Irregular | Compliant | Tilt |
|---|---|---|---|---|---|---|---|
| Natural | Young | 27.3 | 1.1 | 21.6 | 22.7 | 19.3 | 8.0 |
| Column | Young | 15.8 | 6.4 | 22.6 | 23.3 | 16.2 | 15.8 |
| Cross | Young | 19.6 | 3.6 | 21.1 | 26.5 | 15.9 | 13.3 |
| **Totals** | **Young** | **19.2** | **4.2** | **21.5** | **25.3** | **16.3** | **13.5** |
| Natural | Older | 11.1 | 0.9 | 28.2 | 25.6 | 22.6 | 11.5 |
| Column | Older | 12.1 | 7.3 | 23.1 | 21.1 | 17.4 | 19.0 |
| Cross | Older | 14.5 | 3.7 | 22.3 | 22.5 | 22.5 | 14.5 |
| **Totals** | **Older** | **13.1** | **3.9** | **23.9** | **22.9** | **21.3** | **14.9** |

Mean step length demonstrated a significant Age X Condition interaction ($F_{3,54}$ = 5.33, P = 0.003), where post hoc analyses indicated that for each condition older adults had a shorter step length than young adults (Fig. 5.2). A Condition main effect ($F_{3,54}$ = 17.24, P < 0.0001) also showed step length was shortest in the cross condition compared to the rest. Mean step width (see Fig. 5.2) also demonstrated a Condition main effect ($F_{3,54}$ = 45.64, P < 0.0001). Duncan's post hoc testing showed that mean step width was smaller in the control condition versus the column and natural conditions, which were smaller than the cross condition.

### 5.4.2 Stability measures

Age and walking condition influenced the way in which the trunk COM was controlled relative to the lead foot ankle marker (which estimated the edge of the base of support). Older adults' trunk COM was maintained closer to the lead foot ankle marker in the AP direction (AP-SM Age main effect: $F_{1,18}$ = 9.17, P = 0.008) at each foot contact (Fig. 5.3). Independent of age the trunk COM was closer to the ankle markers in the ML direction in the control condition compared to the rest of the conditions (ML-SM Condition main effect: $F_{3,54}$ = 17.35, P < 0.0001).

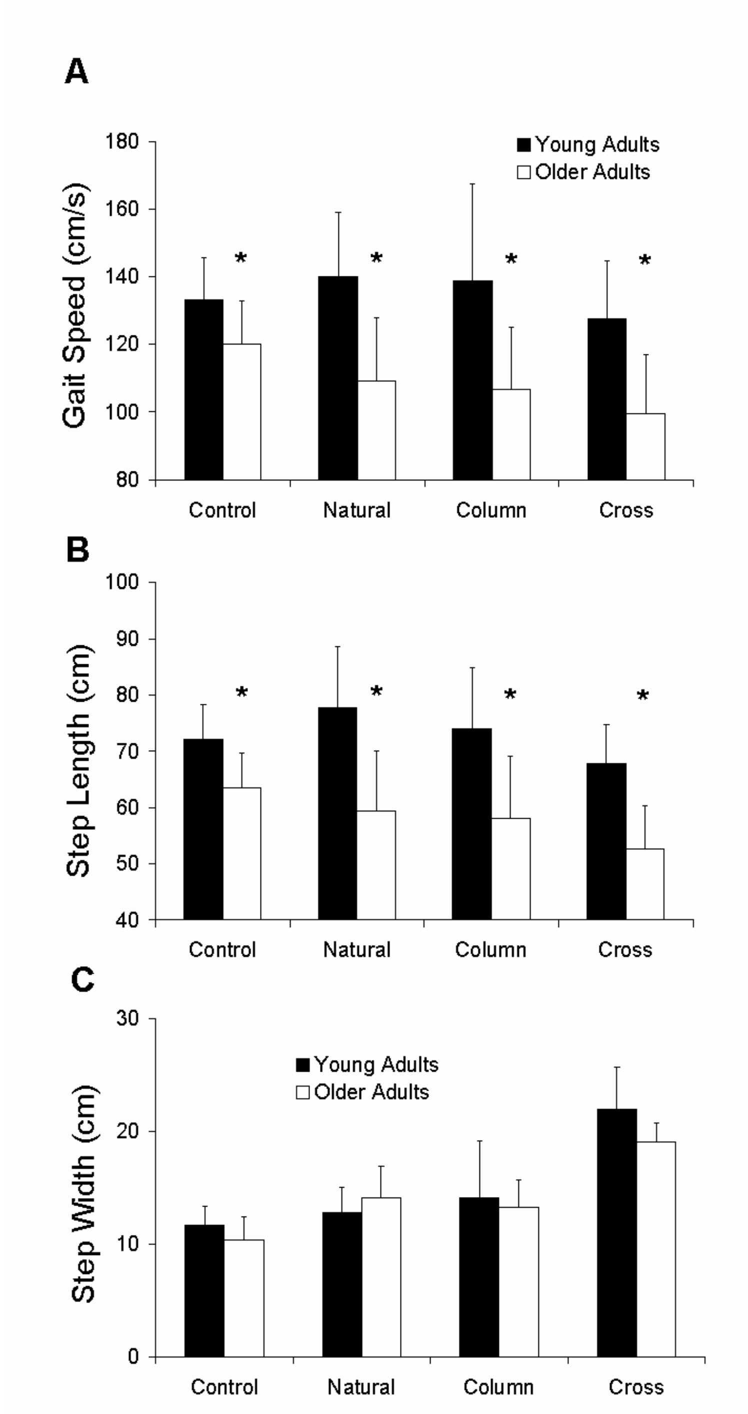



**Figure 5.2:** (A) Gait speed, (B) step length, and (C) step width for the young and older adults while negotiating solid ground terrain or the multi-surface terrain. Asterisks indicate the effects of age ($P < 0.05$).

While the older adults maintained their trunk COM closer to the lead foot ankle marker, their trunk AP COM acceleration RMS (see Fig. 5.4) was significantly diminished compared to the young adults for the column, cross, and natural conditions but not for the control condition (Age X Condition interaction: $F_{3,54} = 7.26$, $P = 0.0004$). Furthermore, a Condition main effect ($F_{3,54} = 24.15$, $P < 0.0001$) demonstrated smaller trunk AP COM acceleration RMS in the control condition compared to the column, cross, and natural conditions. In the ML direction (Fig. 5.4) there was a significant Condition main effect ($F_{3,54} = 25.63$, $P < 0.0001$) with post hoc analyses showing that the trunk ML COM acceleration RMS was largest in the cross condition and smallest in the control condition ($P < 0.05$).

Walking on the different types of ground terrain poses varying degrees of challenge. Thus, it might be anticipated that trunk motion would be compromised compared to walking on a level, uniform surface. In fact, both trunk pitch and trunk roll RMS (see Fig. 5.5) measures demonstrated an Age X Condition interaction ($F_{3,54} = 11.27$, $P < 0.0001$ and $F_{3,54} = 5.65$, $P = 0.002$, respectively). Post hoc analyses indicated that although trunk pitch RMS was larger in the control condition for the young adults, older adults demonstrated larger trunk pitch RMS in the column, cross, and natural conditions on the multi-surface terrain. Similarly, trunk roll RMS was not different between age groups in the control condition; however, the older adults showed larger trunk roll RMS in the column, cross, and natural conditions on the multi-surface terrain compared to the young adults (Fig. 5.5). Trunk pitch and roll RMS also demonstrated Condition main effects ($F_{3,54} = 51.48$, $P < 0.0001$ and $F_{3,54} = 56.05$, $P < 0.0001$, respectively) where RMS values were smallest in the control condition and largest in the cross condition.

It is important to keep the head relatively stable while walking to ensure the visual system can be effective in gathering necessary visual information regarding the environment. The AP head acceleration RMS measure demonstrated a significant Age X Condition interaction ($F_{3,54} = 4.05$, $P = 0.011$). Post hoc tests indicated that only in the column, cross, and natural conditions the RMS values were smaller in the older adults compared to the young adults. In addition, AP ($F_{3,54} = 12.05$, $P < 0.0001$), vertical ($F_{3,54} = 83.26$, $P < 0.0001$), and ML ($F_{3,54} = 9.13$, $P = 0.0002$) head acceleration RMS measures all demonstrated Condition main effects: RMS values were significantly smaller in the control condition compared to the rest.

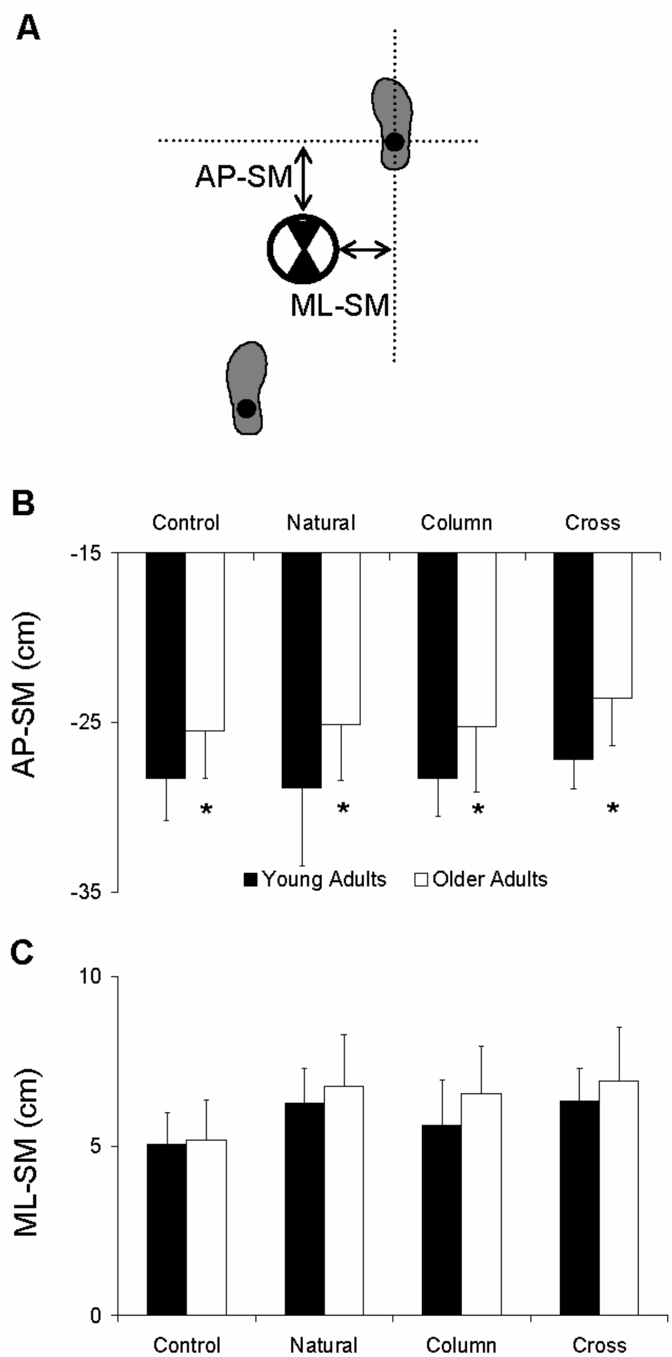



**Figure 5.3:** (A) Illustration of the AP and ML stability margins (SM) demonstrating the relationship between the trunk centre of mass and the ankle marker on the lead foot (an estimate of the edge of the base of support). The (B) AP- and (C) ML-SM are shown for the young and older adults. Error bars represent standard deviation. Asterisks indicate the effects of age ($P < 0.05$).

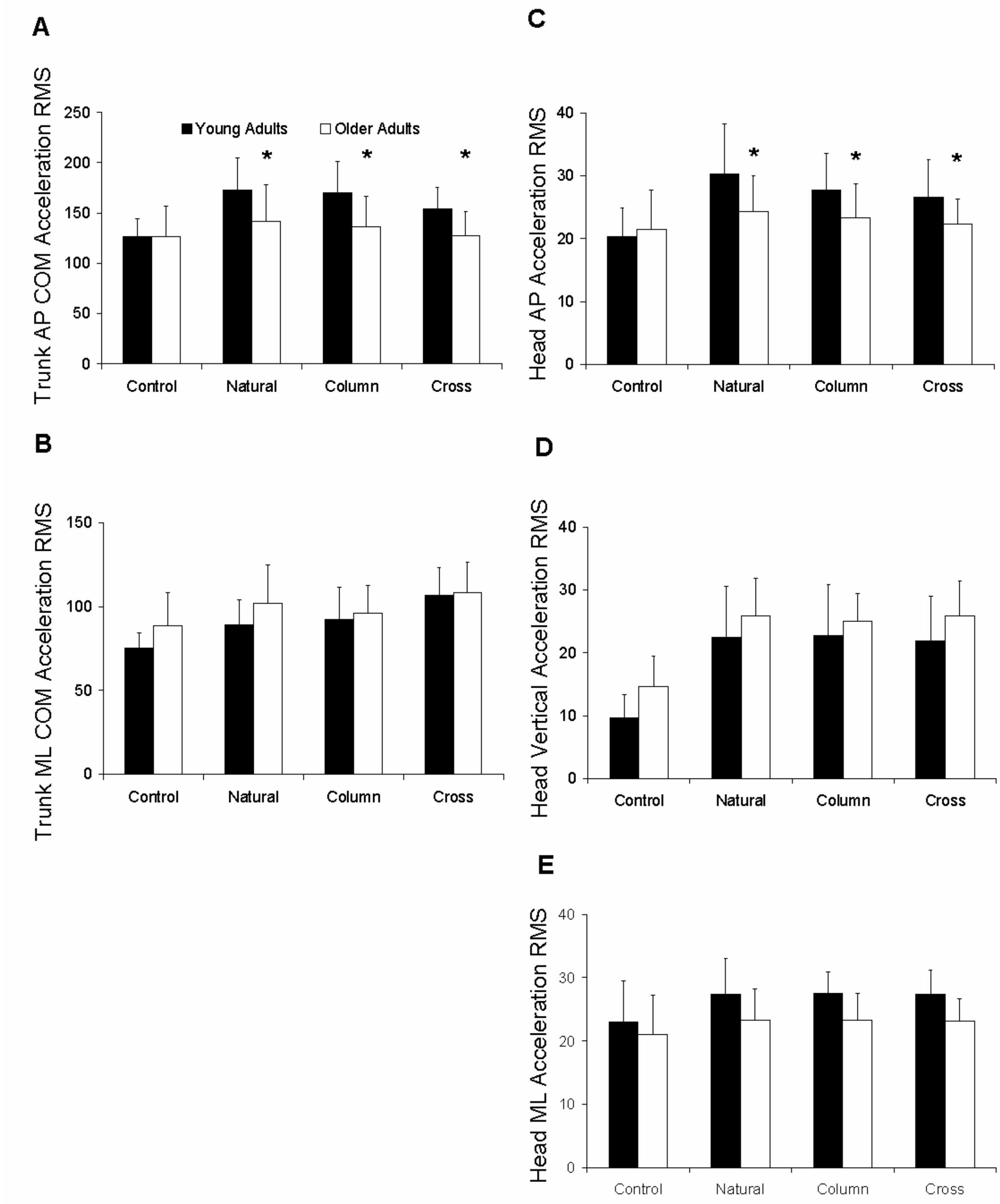



**Figure 5.4:** Trunk and head acceleration RMS for the young and older adults while walking across solid ground terrain or the multi-surface terrain. (A) Trunk AP COM acceleration RMS, (B) trunk ML COM acceleration RMS, (C) head AP acceleration RMS, (D) head vertical acceleration RMS, and (E) head ML acceleration RMS. Error bars represent standard deviation. Asterisks indicate the effects of age ($P < 0.05$).

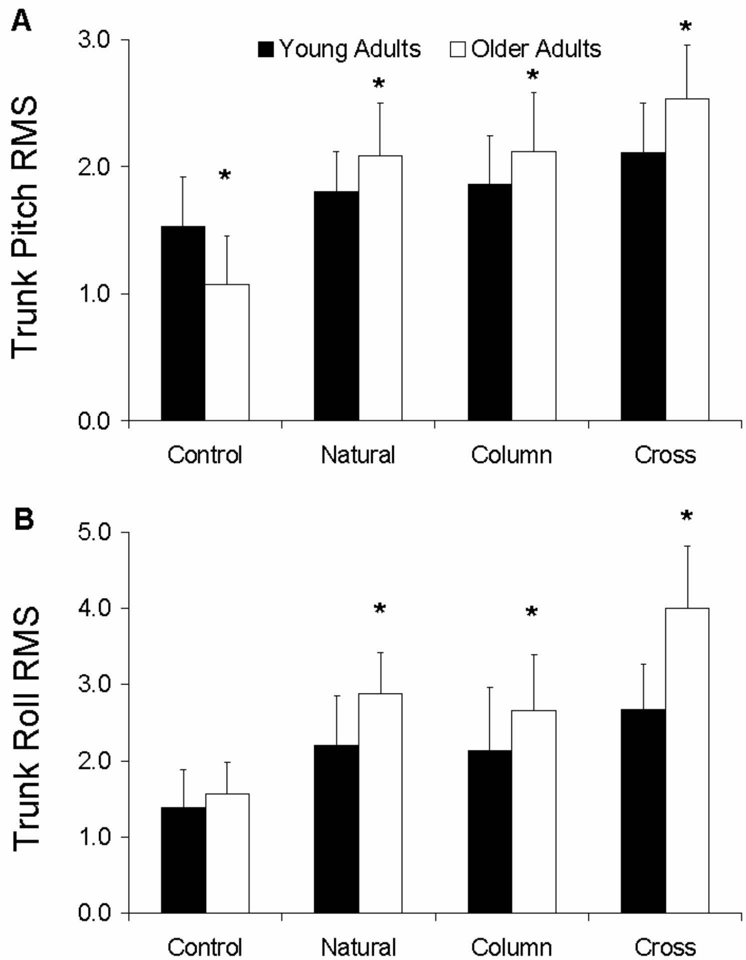



**Figure 5.5:** (A) Trunk pitch angle RMS and (B) trunk roll angle RMS for the young and older adults walking across solid ground terrain or the multi-surface terrain. Error bars represent standard deviation. Asterisks indicate the effects of age ($P < 0.05$).

## 5.5 Discussion

The nervous system must be able to accommodate diverse types of ground terrain as one ambulates in an outdoor environment. Irregularities and differences in frictional and compliant characteristics of these surfaces continually perturb the balance control system. As the bulk of the body's mass is located at the trunk and head and the head houses vital organs including a variety of sensory systems, it is imperative that these regions in particular remain stable (Menz et al. 2003b; Winter 1991). The objective of this study was to determine the effects of aging on stability while negotiating different ground terrain in the same travel path. The results of the stability measures suggest that the nervous system has greater difficulty maintaining stability on challenging ground terrain compared to walking on a solid level path regardless of age. This is reflected by the increases in trunk and head movement while on the multi-surface terrain. For example, trunk pitch and roll RMS were increased when walking on the multi-surface terrain in both young and older adults compared to the control condition. Both Marigold and Patla (2005) and MacLellan and Patla (2006a) have found increased trunk pitch while walking on compliant terrain in young adults. More importantly, the results suggest that older adults are less able to accommodate the multi-surface terrain compared to younger adults. The discussion to follow will expand on this point.

Age-related differences in stability were reflected by several of the measures. Trunk pitch and roll RMS were significantly larger among the older adults compared to the young adults when walking on the multi-surface terrain indicative of increased variability in trunk angle in these directions and/or larger range of motion of the trunk. Helbostad and Moe-Nilssen (2003) have recently reported a relationship between gait speed and ML trunk acceleration: ML trunk acceleration RMS is increased with faster gait speed. Although there were no age effects on ML trunk COM acceleration RMS in our study, older adults did walk significantly slower suggesting that increases in RMS in this direction may have been masked by their slower walking speed. Thus, the combination of these results suggests that older adults had more difficulty maintaining trunk stability compared to young adults. The increased trunk roll RMS among the older adults is particularly concerning given that lateral instability is associated with fall risk (Lord et al. 1999; Maki et al. 1994; Rogers and Mille 2003), older adults often fall to the side (DeGoede et al. 2003; Greenspan et al. 1998; Maki and McIlroy 1996; Rogers and Mille 2003) and laterally directed falls substantially increase the risk of hip fracture (Greenspan et al. 1998; Nankaku et al. 2005; Robinovitch et al. 1991). Lateral instability has also been reported with aging during walking (Woledge et al. 2005) and following perturbations to lateral balance as evident from an increased number of protective steps and greater trunk motion in older adults (Maki et al. 2000; Mille et al. 2005; Rogers and Mille 2003). This instability in older adults may be related, in part, to changes in neuromuscular factors such as reduced hip abductor-adductor torque (Johnson et al. 2004).

Paramount to maintaining dynamic stability and preventing the occurrence of falls is controlling the body COM within the moving base of support defined by the feet (Patla 2003). Our AP and ML stability margins shed light on this control as individuals traversed the multi-surface terrain. Independent of age, the trunk COM remained further from the lead foot in the ML direction while on the multi-surface terrain compared to walking on the solid level surface in the control condition. Positioning the trunk COM closer to the trail limb foot might enhance stability in that the nervous system may first want to 'check' the surface characteristics of the surface stepped on by the lead foot prior to unloading the trail limb which may be on a more stable surface. When a person is aware of an upcoming step on a slippery surface they shift their ML COM closer to the trail limb which is on stable ground compared to the lead limb which is in contact with the slippery surface (Marigold and Patla 2002). This increased safety margin would also serve to protect against lateral falls and maintain ML stability (especially in the older adults who demonstrated greater trunk roll RMS).

The older adults maintained their trunk COM closer to the lead foot in the AP direction at each foot contact on the multi-surface terrain. This was due, in part, to the shorter step length strategy implemented. Bhatt et al. (2006a) have shown that young adults adapt to repeated slip perturbations during walking by shifting their COM further forward at foot contact to increase stability. In contrast, MacLellan and Patla (2006a) have found young adults keep their COM further back from their base of support and maintain a slower forward COM velocity at each foot contact when walking on compliant terrain. These differences, however, may be due to the nature of the task in that individuals may choose to adjust their stability margins differently when making multiple steps on the highly unstable compliant terrain.

While our results appear to indicate stability is compromised among the older adults in terms of trunk angle measures, trunk and head acceleration in the AP direction seems to argue against this notion. Older adults demonstrated smaller trunk and head acceleration variability in the AP direction while walking on the multi-surface terrain compared to the young adults as reflected by attenuated AP trunk COM and head acceleration RMS. Menz et al. (2003a) have also shown reduced head and pelvis acceleration RMS in older adults compared to young adults when walking on irregular terrain. Although these results may seem contrary to what might be expected given the known sensorimotor deficits with increased age, they can partly be explained by the cautious gait strategy adopted by the older adults. This cautious gait strategy consisted of a combination of shorter step length, increased step width, and slower gait speed. This strategy is similar to that observed by Menz et al. (2003a) as older adults walked on irregular terrain. Older adults often walk slower than their younger counterparts (Prince et al. 1997) and slower gait speed is known to decrease trunk and head accelerations (Menz et al. 2003a; Winter 1991). Indeed, we show gait speed is significantly correlated (young and older adults data pooled) with trunk AP COM acceleration RMS (see Fig. 5.6). One other reason for the slower gait speed observed among the older adults may be from impaired visuomotor processing ability. The older adults demonstrated longer durations for completing the Trail Making Test A and B compared to young adults (see Table 2.1).

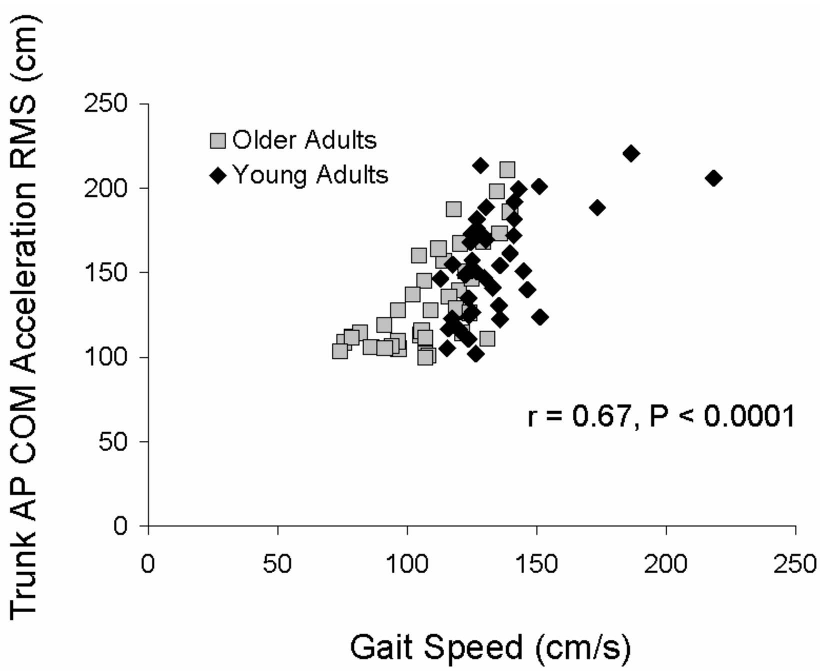



**Figure 5.6:** Relationship between gait speed and trunk AP COM acceleration RMS for the young and older adults. Correlation suggests that trunk AP COM acceleration RMS increases as individuals walk faster.

Gait speed is inversely related to the time to complete these tests (r = -0.64, P = 0.0003 and r = -0.62, P = 0.004 for parts A and B, respectively) such that those individuals who walk slower take longer to complete both parts of the Trail Making Test (see Appendix G). Nonetheless, stability is certainly deteriorated in the ML direction in the older adults.

Despite the fact that our older adults were relatively healthy they were more unstable compared to the young adults. Stability would presumably be more compromised in older adults at a high risk for falls. Indeed, older adults at high-risk for falling show less rhythmic acceleration profiles of the head and pelvis when walking on irregular terrain despite walking slower (Menz et al. 2003c). Thus, further research on the effects of varying ground terrain on stability in older adults is warranted. Interestingly, a recent study by Weerdesteyn et al. (2006) has demonstrated a reduced incidence of falling in older adults following an innovative exercise intervention featuring an obstacle course designed with uneven terrain, different ground surfaces, and challenges to foot placement (e.g. tandem walking and stepping on targets placed at varying locations). In addition, Li et al. (2005) have shown benefits in physical function following cobblestone mat walking in older adults. Moreover, Means and colleagues (Means et al. 2005) have shown that an exercise program focusing on balance, coordination, and strength training leads to reduced falls in the community among older adults and significantly better performance on a functional obstacle course consisting of different types of terrain (e.g. sand and carpet) and environmental challenges (e.g. stairs, ramps, and obstacles).

In conclusion, walking on multi-surface terrain increases the challenge for the nervous system for maintaining balance. Although healthy older adults adopt a cautious walking strategy their stability is decreased, particularly in the ML direction, compared to young adults when negotiating the multi-surface terrain.

### 5.6 Bridging summary

This experiment demonstrates how stability is influenced by walking on multi-surface ground terrain and how healthy aging affects this process. The results from the two studies on gaze fixation patterns suggest that regardless of age individuals fixate approximately two steps ahead in this environment and fixate task-relevant regions to guide their walking. An extension of these experiments pertains to the idea that although individuals are fixating two steps ahead it is also possible that peripheral information from the lower visual field is used. Recent research certainly suggests that visual information from this region may be important for walking. While we are not able to relate all aspects of vision with stability, as it is beyond the scope of this thesis, we focus on the specific question of whether visual information from the lower visual field is needed and how this may or may not affect stability while negotiating varying ground terrain.

## CHAPTER 6 – Visual information from the lower visual field is important for maintaining stability across varying ground terrain

### 6.1 Abstract

Visual information regarding characteristics of the environmental layout is critical for safe navigation. The purpose of this study was to determine whether vision from the lower visual field was important for negotiating varying ground terrain. Additionally, we were interested in whether age influenced this need. Ten healthy young and ten healthy older adults walked across a walkway where the middle portion consisted of varying ground terrain (i.e. solid, rock, slippery, compliant, uneven, and irregular). Participants performed the walking trials with and without special glasses that blocked the lower visual field. Kinematic data was recorded from position markers on the ankles, trunk, and head to measure trunk and head stability and to determine whether individuals tilted their head down to see the ground when wearing the glasses that blocked the lower visual field. Both young and older adults demonstrated increased mean and maximum head pitch angle downward when wearing the glasses that blocked the lower visual field suggesting the importance of vision from this area when stepping on multi-surface terrain. Trunk and head acceleration root-mean-square (RMS) deviation values were smaller when the lower visual field was blocked, although this was likely due to the cautious gait strategy (i.e. slower gait speed and shorter step length) adopted by both young and older adults. Trunk pitch RMS was, however, increased when vision was occluded in the lower visual field regardless of age. The results have implications for those individuals who wear multi-focal glasses and who use them while walking in complex environments with different types of ground terrain, which may challenge balance.

### 6.2 Introduction

The nervous system receives a multitude of visual information as an individual traverses through an environment with diverse ground terrain. This information must be integrated with other sensory input to facilitate safe travel. Several studies have illustrated the importance of using visual information in an on-line manner to guide locomotion; that is visual input obtained as an individual interacts with the environment is used in real-time to modify locomotion (Fajen and Warren 2003; Marigold and Patla 2007; Mohagheghi et al. 2004; Patla and Greig 2006; Patla and Vickers 2003; Patla 1998; Rietdyk and Rhea 2006). Visual information sampled on-line is critical for adjusting foot placement during the approach phase preceding obstacle avoidance (Patla and Greig 2006) and visual information regarding limb trajectory and step target location are used on-line to adjust foot placement during rapid stepping movements (Reynolds and Day 2005).

While people tend to fixate approximately two steps ahead when walking in an environment with challenging ground terrain or stepping to targets placed along the travel path (Marigold and Patla 2007; Patla and Vickers 2003), visual information can be extracted covertly by peripheral vision from the lower visual field and serve to modify lower limb trajectory and/or foot placement when required. Visual input relating the position of the lower limb to the ground immediately in front is referred to as visual exproprioception and is important for obstacle avoidance (Patla 1998; Patla et al. 2004; Rietdyk and Rhea 2006). When this information is blocked during the step over an obstacle, toe clearance, toe clearance variability, and foot placement before the obstacle are all increased (Patla 1998). In addition, Marigold et al. (2007) have demonstrated that peripheral vision from the lower visual field is sufficient for stepping over unexpected obstacles during locomotion on a treadmill: gaze is not re-directed to the obstacle or landing area. Interestingly, reaches made towards targets are more accurate when performed in the lower visual field compared to the upper visual field (Danckert and Goodale 2001; Khan and Lawrence 2005), although this has recently been questioned (Krigolson and Heath 2006). Nonetheless, we still know little about how the nervous system utilizes peripheral vision for locomotion in the context of more complex environments.

Visual function declines with age as reflected by impaired contrast sensitivity, binocular visual acuity, depth perception, and reduced useful field of view compared to young adults, which significantly increases the risk of falls in older adults (Black and Wood 2005; Coleman et al. 2004; Haegerstrom-Portney et al. 1999; Lord 2006; Owsley et al. 1995; Watson 2001). These visual deficits also impact greatly on physical functioning (West et al. 2002). Loss of the visual field in older adults is associated with an increased number of bumps into objects on a mobility course (Turano et al. 2004). When vision is blurred by light scattering lenses (which reduces contrast sensitivity to that of a dense cataract), older adults alter how they step down from a stair (Buckley et al. 2005a,b). Specifically, step execution time is increased, greater weight is supported by the contralateral (non-stepping) limb, and medial-lateral (ML) stability is reduced (Buckley et al. 2005a,b).

Many older adults require corrective lenses to function in everyday life. Multi-focal (bifocal, trifocal, or progressive) glasses pose a risk for falling for older adults when negotiating varying ground terrain, obstacles, and stairs (Lord 2006). Viewing the environment through the lower portion of the lens impairs contrast sensitivity and depth perception, which are important for detecting hazards (Lord et al. 2002; Lord 2006). In fact, fall risk is significantly increased in older adults who wear multi-focal glasses compared to those that don't (Lord et al. 2002).

Despite the fact that fall risk is increased in individuals who wear multi-focal glasses, little is known about how the nervous system utilizes vision from the lower visual field to guide foot placement and maintain balance when walking in complex environments consisting of challenging ground terrain. Thus, we asked the following questions. To what extent is stability affected by the inability to properly see the lower visual field while walking? Is visual exproprioceptive information from the lower visual field necessary for walking on diverse ground terrain? Does age influence the need to use peripheral vision from the lower visual field in this context?

## 6.3 Methods

### 6.3.1 Participants

Ten healthy young adults (5 female, 5 male; mean ± SD age = 26.1 ± 5.2 yrs.) and ten healthy older adults (5 female, 5 male; mean ± SD age = 74.1 ± 7.2 yrs.) volunteered for this study. Participants did not have any neurological, muscular, or joint disorder that could affect their performance and/or behaviour in this study. Participants wore corrective lenses if necessary: no participants wore multi-focal lenses. Visual testing consisting of binocular visual acuity and binocular contrast sensitivity were performed using a Bailey-Lovie type logMAR chart read at 6.3 meters (and thus providing a range of 0.8 to -0.5 log MAR) and a Pelli-Robson contrast sensitivity chart read at 1 meter, respectively. Additionally, the visual field was tested both with and without the glasses (see description below) that occluded the lower visual field. A self-reported 6-month retrospective fall history was also determined. Balance confidence, functional mobility, and visuomotor processing ability were assessed using the Activities-specific balance confidence (ABC) scale (Powell and Myers 1995), timed up and go test (Podsiadlo and Richardson 1991),

**Table 6.1:** Participant characteristics.

| Characteristics* | Young Adults (N = 10) | Older Adults (N = 10) |
|---|---|---|
| **Age, years** | 26.1 ± 5.2 (20 - 37) | 74.1 ± 7.2 (61 - 82) |
| **Gender, Male/Female** | 5/5 | 5/5 |
| **Binocular Acuity, logMAR** | -0.3 ± 0.1 (-0.5 to -0.1) | 0 ± 0.2 (-0.3 to 0.5) |
| **Binocular Contrast Sensitivity, log** | 1.7 ± 0.1 (1.65 - 1.95) | 1.6 ± 0.1 (1.35 - 1.65) |
| **Timed Up and Go, seconds** | NA | 9.7 ± 1.9 (8.0 - 13.6) |
| **ABC scale, %** | 96.4 ± 3.5 (88.1 - 100) | 93.4 ± 7.1 (81.9 - 100) |
| **Trail Making Test A, seconds** | 16.3 ± 2.5 (12.9 - 19.3) | 31.0 ± 10.7 (20.8 - 51.4) |
| **Trail Making Test B, seconds** | 35.6 ± 14.6 (24.4 - 75.1) | 65.6 ± 28.1 (44.0 - 138.4) |
| **# of Fallers** | 2 | 1 |

*Date are mean ± SD (range)

NA = not available

and the Trail Making Test (part A and B) (Tombaugh 2004), respectively, to provide an overall picture of the abilities of the young and older adults (see Table 6.1).

The study was approved by the Office of Research Ethics at the University of Waterloo and informed written consent was received from all participants.

### 6.3.2 Protocol

Participants were required to walk at a self-selected pace along a painted (medium shade of grey) wooden walkway (~8.5 m long, ~1.5 m wide and elevated ~0.1 m) where six different types of ground terrain (2 solid, 3 compliant, 3 rocky, 3 irregular, 3 tilt, and 1 slippery), each 0.5 m x 0.5 m, formed a 5 x 3 grid of 15 surfaces (i.e. multi-surface terrain section) in the middle portion (~2.5 m long) (see Fig. 6.1). The solid, tilt, and irregular surfaces were painted the same color as the walkway. The solid surfaces were constructed the same as the rest of the walkway and posed no challenge. The rocky surfaces were composed of a bed of small irregularly shaped rocks (ranging in size from 1 x 1.5 cm to 2 x 5 cm). The tilt (or uneven) surfaces were constructed such that they had a 10º downward tilt (either to the left or right in the frontal plane) and are referred to as Tilt – L or R. The slippery surface was made of a piece of white ultra-high molecular weight polyethylene (used for artificial ice) mounted on a wooden base. The irregular surfaces had irregularly spaced custom-made dark grey rock-climbing holds mounted on the top. The height of these rock-climbing holds ranged from 1 to 3 cm and the spacing between holds ranged from 2 to 5 cm. The compliant surfaces were composed of medium-density foam (maximum compression of ~0.08 m; stiffness ~13 kN/m) and covered with a thin green fabric (to simulate wet, soggy, grass). Each participant wore a full-body safety harness attached to a friction-less trolley (via a dynamic rock-climbing rope) mounted to an I-beam along the ceiling of the laboratory.

There were two visual conditions: normal vision and peripheral vision from lower visual field occluded (LVF). In the LVF condition, peripheral vision from the lower visual field was occluded by having participants wear glasses (without lenses) where the lower portion was blocked (see Appendix H). Participants performed eight walking trials (four with normal vision and four with the lower visual field blocked) at the start of the experiment where the entire walkway consisted of a uniform solid surface (i.e. control walking) and walked to an end goal. There were three different multi-surface terrain configurations in which participants had to walk across in subsequent walking trials for the young adults and only two different configurations for the older adults (see Appendix A). There were fewer configurations for the older adults to reduce the number of walking trials due to time and fatigue constraints. The two/three configurations were constructed based on two factors: (1) there were 2 solid, 1 slippery, 3 compliant, 3 rocky, 3 irregular and 3 tilt surfaces available (chosen to represent commonly encountered ground terrain and fit the size of the experimental set-up and laboratory space available) for each configuration and (2) the rocky, compliant, and irregular surfaces were always grouped with their other two respective surfaces (see Fig. 6.1 and Appendix A). A board obstructed the participant's view of the multi-surface terrain configuration prior to the start of each trial. Following a 'go' signal, the board obstructing the participant's view was removed and they began to walk such that they took around four steps before reaching the multi-surface terrain section (approximately 3 – 4 seconds). The path to walk across the multi-surface terrain was manipulated such that there were three conditions (see Fig. 6.1): column, cross, and natural. In the natural condition, participants were free to choose which surfaces to step on. In the other two conditions, two sets of two vertical posts were positioned on either side the appropriate surface of the first and last row of the multi-surface terrain configuration and participants were required to walk through them. Between the posts participants were free to choose which surfaces to step on. In the column conditions, the vertical posts were positioned along the left, centre, or right column of the multi-surface terrain. In the cross conditions, participants had to cross over one or two columns of the multi-surface terrain such that there were the following combinations within this condition: start left/end centre, start left/end right, start centre/end left, start centre/end right, start right/end centre, and start right/end left. However, regardless of the conditions, participants were instructed to walk to an end goal marked with an 'x' on a piece of white paper mounted on the end of the walkway and visible throughout the trial. The three conditions were randomly presented within each multi-surface terrain configuration. Each block of trials of a particular configuration was presented once in random order for each vision condition (Appendix F).

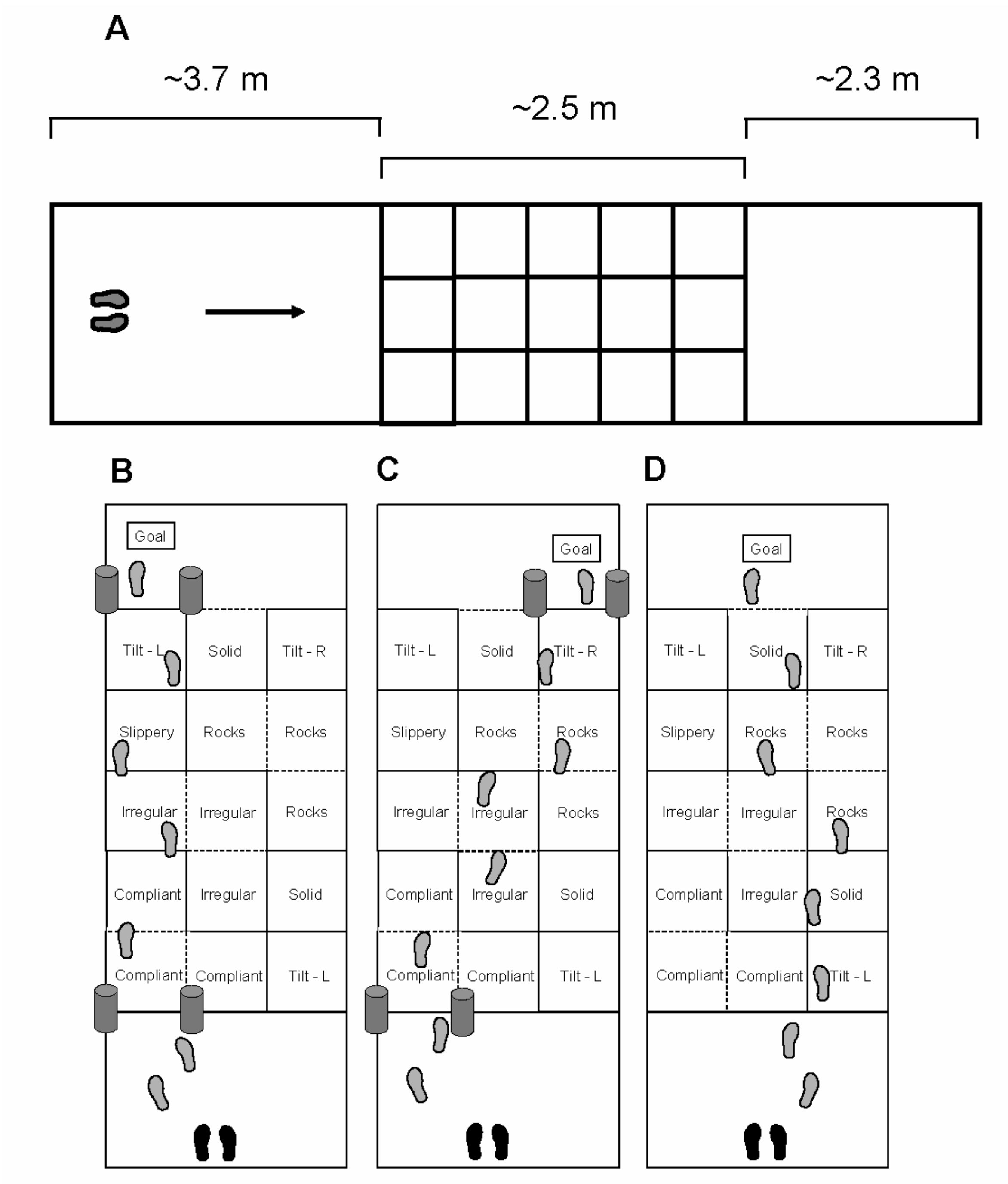



**Figure 6.1:** Experimental set-up (A) and protocol (B-D) for the multi-surface terrain configurations. (B) Column condition where the gates are set at the beginning and end of the left (as shown), centre, or right column of the multi-surface terrain section. (C) Cross condition where the gates are set at the beginning and end of different columns (start left – end right condition shown). (D) Natural condition where there were no gates present and participants could step on any surface.

Three Optotrak cameras were used to collect kinematic data (sampling frequency of 60 Hz) and a video camera recorded the walking trials from the left side of the participant's body for qualitative observations. Position markers (infrared emitting diodes) were placed bilaterally on the ankles, iliac crests, and sternal end of the clavicles, as well as on the xyphoid process, chin, and head. For the head, a plastic band was used that contained a cluster of five markers centered on the forehead and a marker close to the left ear. The cluster of position markers was important as this way at least one marker was visible to the cameras regardless of where the participant moved their head. A custom-written program in MATLAB low-pass filtered the position data for all markers at 6 Hz ($2^{nd}$ order, dual-pass, Butterworth algorithm) and processed all kinematic data.

### 6.3.3 Coordinate frames

The coordinate frames which describe the motion of the body, trunk, and head while moving through space were defined in a hierarchical manner as described by Courtine and Schieppati (2003) and Imai et al. (2001). The primary coordinate frame was the spaced-fixed reference frame of the Optotrak system ($X_S$, $Y_S$, $Z_S$) of the body relative to space, the vertical axis ($Y_S$) of which was parallel to the direction of gravity (positive being upwards), the anterior-posterior (AP) axis ($X_S$) was parallel to the direction of straight walking (positive being forward) and orthogonal to the $Y_S$-axis, and the ML axis ($Z_S$) was positive to the participant's right and orthogonal to the $X_S$-$Y_S$ plane. While walking in this task the body follows a trajectory in the $X_S$-$Z_S$ plane, which can be determined by the linear motion of a point on the body ($x_s$, 0, $z_s$). To investigate the movements of the trunk and head in space a trajectory coordinate ($X_T$, $Y_T$, $Z_T$) frame was defined, the vertical axis ($Y_T$) of which was parallel to the vertical axis of spatial coordinate frame ($Y_S$). Trunk centre of mass (COM) was calculated from the iliac crest, xyphoid, and clavicle position markers using anthropometric data and segment definitions from Winter (2005). The linear velocity of the trunk COM in the $X_S$-$Z_S$ plane at each point of the trajectory determined the $X_T$-axis of the trajectory coordinate frame, which as in the direction of walking. This was defined as the heading direction whose rotation angle with respect to the spatial coordinate frame was calculated as follows (Courtine and Schieppati 2003):

$$\theta_T = Tan^{-1}\left(\frac{Z_T}{X_T}\right)$$

where the angle θ defines the heading of the trunk COM in space at any point on the trajectory. The heading angle was positive for a right turn. Subsequently, any vectors in the spatial coordinate frame could be converted to the trajectory coordinate frame through multiplication by the transformation matrix $R_T$ (Courtine and Schieppati 2003):

$$R_T = \begin{bmatrix} \cos\theta_T & 0 & \sin\theta_T \\ 0 & 1 & 0 \\ -\sin\theta_T & 0 & \cos\theta_T \end{bmatrix}$$

Trunk and head angles relative to the trajectory coordinate frame were calculated from the transformed trunk and head position markers. Trunk pitch was calculated as the angle between a vertical line (parallel to the $Y_T$-axis) and a line joining the bisection of the iliac crest markers and bisection of the clavicle markers parallel to the $X_T$-axis. As the trajectory coordinate frame was determined from the trunk COM, the head relative to the trajectory coordinate frame can also be referred to as head relative to trunk. Head pitch was calculated as the angle between a vertical line (parallel to the $Y_T$-axis) and a line joining the head (single marker from the cluster on the forehead) and chin position markers parallel to the $X_T$-axis. Thus, trunk and head pitch movements were around the $Z_T$-axis, where head pitch downward and trunk pitch forward were positive. Trunk roll was calculated as the angle between a vertical line (parallel to the $Y_T$-axis) and a line joining the bisection of the iliac crest markers and bisection of the clavicle markers parallel to the $Z_T$-axis. Thus, movements were around the $X_T$-axis, where trunk roll to the right was positive.

### 6.3.4 Data analysis

Foot contacts on the multi-surface terrain (or control condition equivalent) were determined based on the displacement profiles of the ankle markers using a computer algorithm in conjunction with visual inspection. The mean step length and width (based on the displacement data of the ankle markers) were calculated along with gait speed across the multi-surface terrain (or control condition equivalent), which was based on the displacement data of the xyphoid position marker.

The AP and ML trunk COM accelerations were determined by double differentiating the AP and ML COM displacement data and AP, vertical, and ML head accelerations were determined by double differentiating a single head position marker (from the cluster of markers on the head-piece). AP and ML stability margins (SM) based on the location of the trunk COM and ankle position markers (an estimate of the edge of the base of support) were also determined at each foot contact on the multi-surface terrain (or control condition equivalent) and subsequently averaged. The ML-SM was calculated by subtracting the ML ankle marker position of the lead foot from the ML trunk COM position and corrected based on which foot was leading so that positive values indicated the ML trunk COM medial to the lead foot. The AP-SM was calculated by subtracting the lead foot AP ankle marker position from the AP trunk COM position such that negative values indicated the trunk COM behind the lead foot with values approach zero representing the COM coming closer to the ankle marker of the lead foot.

The trunk AP and ML COM accelerations, head accelerations, and trunk and head angles were determined from foot contact on the first surface of the multi-surface terrain until foot lift-off from the last surface of the multi-surface terrain. Subsequently, the root-mean-square (RMS) deviation (i.e. standard deviation) was calculated for each measure during this time interval and reflected trunk and head stability while walking on the multi-surface terrain. Additionally, the mean and maximum head pitch angle during this time interval was determined. These measures, in particular, capture the need to use peripheral visual information from the lower visual field: a larger mean and/or maximum head pitch angle downward during the LVF condition would suggest that the nervous utilizes information from lower visual field.

### 6.3.5 Statistical analysis

The data were rank transformed, where appropriate, if the data was not normally distributed (as determined by examination of normality plots in conjunction with the Kolmogorov-Smirnov test for normality).

A three-way ANOVA with Age (young and old) as a between-subject factor and Condition (control, column, cross, and natural) and Vision (normal and LVF) as the within-subject factors was performed for all measures. These measures included gait speed, mean step length and width, AP-SM, ML-SM, trunk AP and ML COM acceleration RMS, trunk pitch and roll RMS, head pitch RMS, mean and maximum head pitch, and AP, vertical, and ML head acceleration RMS. Duncan's and LS-means post hoc tests were performed for the main effects and interactions, respectively, when significant. As the preceding chapter has reported the results based on the normal vision condition, we will focus only on the Vision main effects (and Age main effects of the head pitch measures) and Vision X Age, Condition X Vision, and Age X Vision X Condition interactions in this study.

An alpha level of 0.05 was chosen for significance for all statistical analyses.

## 6.4 Results

There were no falls among the young and older adults while walking across the multi-surface terrain. The extent of the lower visual field of the young and older adults (average of both eyes) without the special glasses was 58.2° ± 6.7° and 60.9° ± 12.6° eccentricity (when fixating perpendicular to the ground), respectively, along a vertical axis (parallel to the direction of gravity). In contrast, when wearing the special glasses young and older adult's lower visual field was only 29.5° ± 8.5° and 18.2° ± 9.3° eccentricity, respectively.

### 6.4.1 Effect of blocking lower visual field on head movements

Blocking the lower visual field while walking on the multi-surface terrain dramatically altered head movements (Fig. 6.2). There was a Vision X Condition interaction ($F_{3,54}$ =

3.48, $P = 0.022$) and Vision ($F_{1,18} = 25.51$, $P < 0.0001$) and Age ($F_{1,18} = 13.5$, $P = 0.002$) main effects for mean head pitch angle. There was also a Vision ($F_{1,18} = 22.68$, $P = 0.0002$) and Age ($F_{1,18} = 11.06$, $P = 0.004$) main effect for maximum head pitch angle. Specifically, mean and maximum head pitch angles were increased by approximately 7° and 9°, respectively, in the LVF condition compared to the normal vision condition. Mean head pitch angle was increased in the LVF condition for the control, column, cross, and natural cases. Furthermore, mean and maximum head pitch angles were greater in the older adults compared to the young adults. Additionally, head pitch RMS was significantly increased in the LVF condition (Vision main effect: $F_{1,18} = 10.15$, $P = 0.005$), which may have been larger due to the increased frequency of looking down at the multi-surface terrain.

AP, vertical, and ML head acceleration RMS measures (Table 6.2) all demonstrated Vision main effects ($F_{1,18} = 9.99$, $P = 0.005$; $F_{1,18} = 19.71$, $P = 0.003$; $F_{1,18} = 14.95$, $P = 0.001$, respectively). RMS was decreased in the LVF condition for the AP and ML direction but increased in the vertical direction. There was also a Vision X Condition interaction ($F_{3,54} = 4.00$, $P = 0.012$) for the AP head acceleration RMS where the RMS values were increased in the normal vision condition compared to the LVF condition for the column, cross, and natural conditions only.

### 6.4.2 The effect of blocking the lower visual field on trunk movements

Illustrated in Fig. 6.3 are the effects of blocking the lower visual field on trunk acceleration and trunk pitch and roll measures. Trunk AP COM acceleration RMS demonstrated a main effect of Vision ($F_{1,18} = 5.69$, $P = 0.028$). The RMS was larger in the normal vision condition compared to the LVF condition. There were no effects of vision on trunk ML COM acceleration RMS ($P > 0.05$).

Trunk pitch RMS demonstrated a main effect of Vision ($F_{1,18} = 11.42$, $P = 0.003$) where the RMS was greater than when the lower visual was blocked by the special glasses. Trunk roll RMS showed a Vision X Condition interaction ($F_{3,54} = 2.86$, $P = 0.045$) where only in the cross condition was the RMS greater in the LVF condition compared to the normal vision condition. Additionally, there was an Age X Vision X Condition interaction ($F_{3,54} = 3.65$, $P = 0.\ 018$) for trunk roll RMS (see Fig. 6.3).

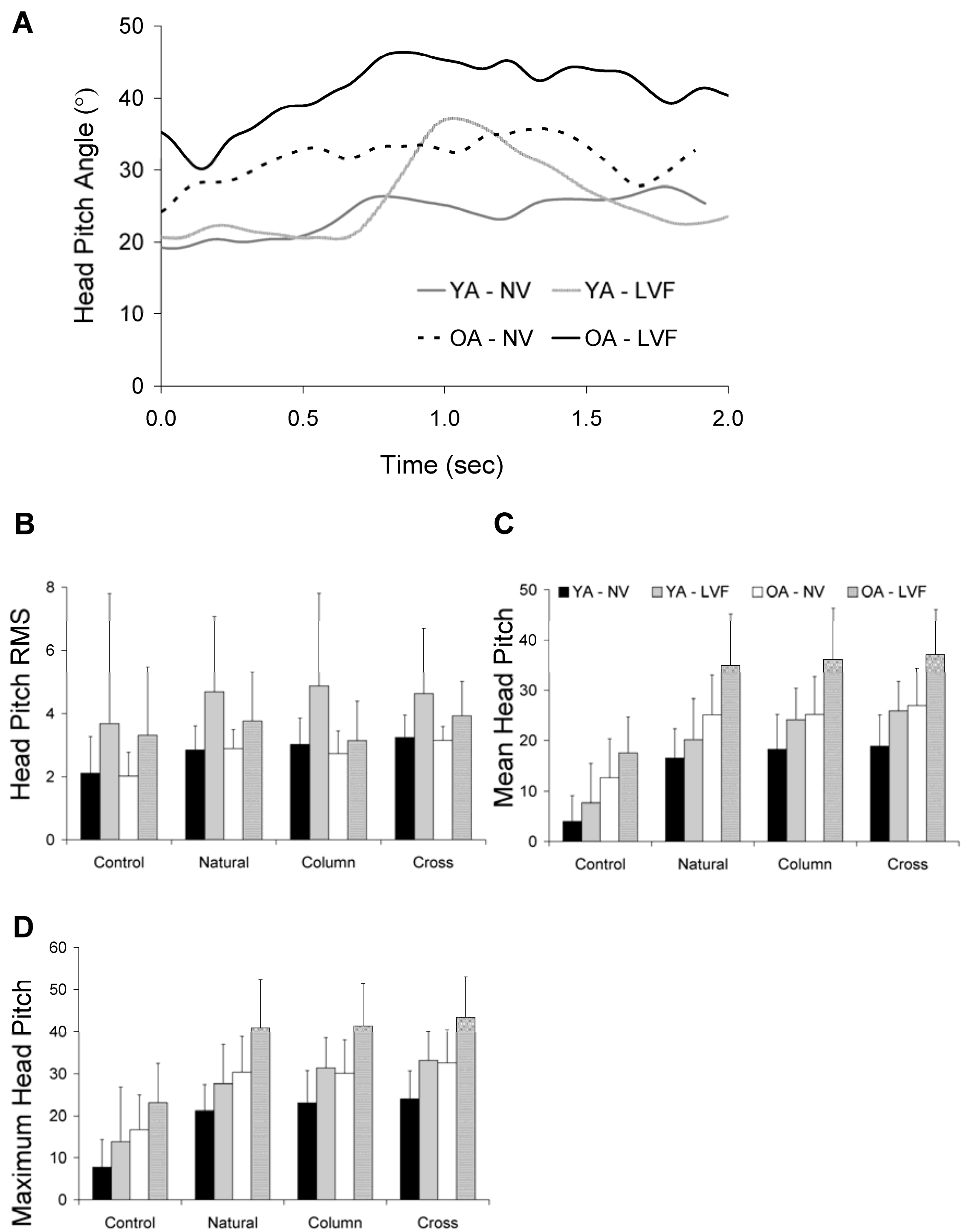



**Figure 6.2:** Head pitch angle changes when the lower visual field was blocked while walking on the multi-surface terrain for the young (YA) and older (OA) adults. (A) Representative trials of head pitch angle for one young and one older adult with and without the lower visual field blocked while walking. Head pitch angle (B) RMS, (C) mean, and (D) maximum. NV = normal vision. LVF = lower visual field blocked. Error bars represent standard deviation.

**Table 6.2:** Head acceleration RMS (cm) measures.

| Age | Vision | Condition | AP Acceleration | Vertical Acceleration | ML Acceleration |
|---|---|---|---|---|---|
| Young | Normal | Control | 20.3 ± 4.6 | 9.7 ± 3.7 | 23 ± 6.6 |
| Young | Normal | Natural | 30.3 ± 8.0 | 22.4 ± 8.2 | 27.4 ± 5.6 |
| Young | Normal | Column | 27.7 ± 5.9 | 22.8 ± 8.1 | 27.5 ± 3.4 |
| Young | Normal | Cross | 26.6 ± 5.9 | 21.9 ± 7.1 | 27.4 ± 3.8 |
| Young | LVF | Control | 21.1 ± 4.8 | 11.7 ± 4.2 | 20.8 ± 3.5 |
| Young | LVF | Natural | 28 ± 6.4 | 24.8 ± 8.1 | 25.9 ± 4.7 |
| Young | LVF | Column | 25.2 ± 6.0 | 24.3 ± 4.1 | 25.3 ± 3.9 |
| Young | LVF | Cross | 24.7 ± 6.3 | 25.7 ± 4.9 | 24.7 ± 3.8 |
| Older | Normal | Control | 21.5 ± 6.3 | 14.7 ± 4.8 | 21.0 ± 6.2 |
| Older | Normal | Natural | 24.3 ± 5.8 | 25.9 ± 5.9 | 23.3 ± 4.9 |
| Older | Normal | Column | 23.3 ± 5.5 | 25.0 ± 4.4 | 23.3 ± 4.3 |
| Older | Normal | Cross | 22.3 ± 4.1 | 25.8 ± 5.6 | 23.2 ± 3.5 |
| Older | LVF | Control | 20.7 ± 4.5 | 16.7 ± 3.8 | 18.8 ± 5.7 |
| Older | LVF | Natural | 19.8 ± 4.1 | 30.6 ± 6.3 | 22.2 ± 3.6 |
| Older | LVF | Column | 18.8 ± 4.3 | 29.4 ± 5.2 | 20.6 ± 4.4 |
| Older | LVF | Cross | 18.8 ± 3.3 | 30.8 ± 6.2 | 21.7 ± 3.1 |

LVF = lower visual field occluded condition

Interestingly, the trunk COM was closer to the base of support (estimated from an ankle marker) of the lead foot in both the AP and ML directions in the normal vision condition compared to when the lower visual field was blocked. This was reflected in a Vision main effect for the AP-SM ($F_{1,18} = 9.69$, $P = 0.006$) and the ML-SM ($F_{1,18} = 15.06$, $P = 0.001$). Specifically, the AP-SM in the normal vision condition was -26.5 ± 3.5 cm versus -27.4 ± 3.2 cm in the LVF condition. The ML-SM in the normal condition was 6.1 ± 1.4 compared to 6.6 ± 1.6 in the LVF condition.

### 6.4.3 The effect of blocking the lower visual field on step parameters and gait speed

The young and older adults both walked slower when the lower visual field was blocked as reflected by a Vision X Condition interaction ($F_{3,54} = 3.29$, $P = 0.027$) and Vision main effect ($F_{1,18} = 19.66$, $P = 0.0003$) of gait speed (Fig. 6.4). The mean step length (Vision main effect: $F_{1,18} = 14.38$, $P = 0.001$) was also decreased in the LVF condition compared to normal vision. Additionally, there was a three-way Age X Vision X Condition interaction for mean step width ($F_{3,54} = 3.60$, $P = 0.019$). Post hoc analyses indicated that in the LVF condition, young adults step width was increased compared to the older adults in the natural condition only ($P = 0.019$).

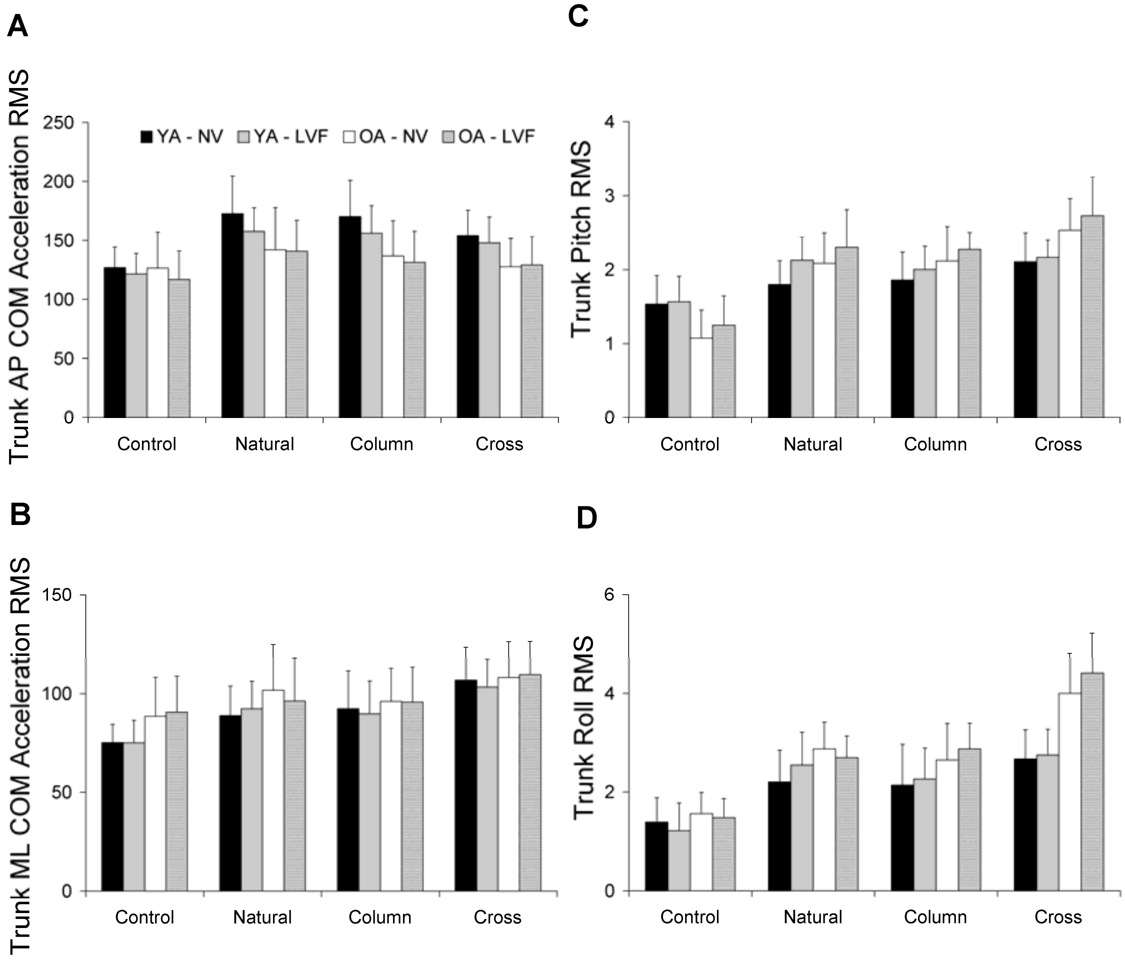



**Figure 6.3:** Trunk stability measures for the young (YA) and older (OA) adults while walking on solid ground terrain or the multi-surface terrain with (LVF) and without (NV) the special glasses that block the lower visual field. (A) Trunk AP COM acceleration RMS, (B) trunk ML COM acceleration RMS, (C) trunk pitch angle RMS, and (D) trunk roll angle RMS are shown. Error bars represent standard deviation.

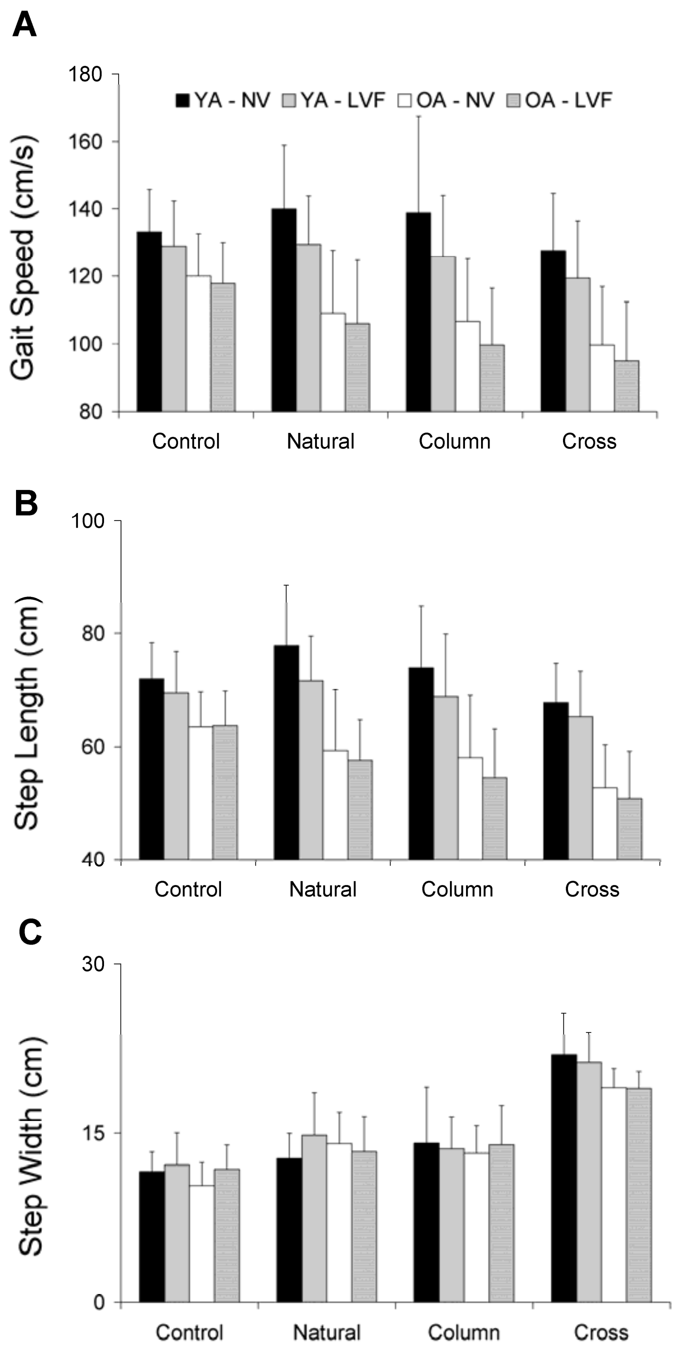



**Figure 6.4:** (A) Gait speed, (B) step length, and (C) step width for the young (YA) and older (OA) adults while negotiating solid ground terrain or the multi-surface terrain with (LVF) and without (NV) the special glasses that block the lower visual field. Error bars represent standard deviation.

### 6.5 Discussion

We sought to determine the effects on stability from occluding peripheral vision from the lower visual field while walking on varying ground terrain. In addition, we questioned whether visual input from this region was necessary and whether advancing age influenced this potential need. Our results suggest that regardless of age visual information from the periphery, in particular the lower visual field, is critical to ensure stability when negotiating hazardous ground terrain. On-line monitoring of the lower limb and ground immediately in front may be beneficial to optimize foot placement and to ensure one is able to adapt to stability concerns, unexpected changes in terrain, or sudden changes in the path taken. The near periphery is good at texture segmentation (Joffe and Scialfa 1995) and thus, may be useful in distinguishing the different surfaces across the multi-surface terrain.

When peripheral vision was blocked both young and older adults demonstrated significantly greater head pitch downward in an attempt to improve vision of the ground. This was reflected by the increases in mean and maximum head pitch angle. Thus, visual information from the lower visual field seems to be necessary while walking across these surfaces. Marigold et al. (2007) have recently shown that when an obstacle is suddenly released onto a moving treadmill while a person is walking and fixating a point approximately two steps ahead, individuals do not re-direct gaze to the obstacle. Rather, they maintain central vision on the target ahead and utilize peripheral vision from the lower visual field to detect the obstacle and make the necessary changes to limb trajectory to avoid the obstacle. On-line visual information of the lead limb and obstacle location for stepping over obstacles in the travel path is important for both successful clearance and controlling lead and trail limb foot placement (Mohagheghi et al. 2004; Patla 1998; Rietdyk and Rhea 2006). Indeed, individuals with peripheral visual field loss due to retinitis pigmentosa have decreased mobility performance compared to normally sighted individuals as demonstrated by an increased number of mobility incidents (contacts with objects, stumbling and neglecting to detect stairs) and slower gait speed (Geruschat et al. 1998).

While we have previously shown that individuals fixate approximately two steps ahead when walking on the multi-surface terrain (Marigold and Patla 2007), it is highly possible that they are attending to both the fixation area and specific regions within the lower visual field to guide subsequent actions. In this sense, individuals may be obtaining on-line visual information of the ground terrain ahead to plan subsequent steps while at the same time monitoring their current step (and terrain in which they are in contact with) and lower limb trajectory. We would argue that people rapidly switch attention between the point of fixation and the lower visual field in the periphery while walking on the multi-surface terrain depending on the current or future step. For example, challenging upcoming terrain might require visual attention directed to the point of fixation ahead to facilitate planning of the step whereas attention may be directed to the lower visual field to monitor the immediate step (i.e. foot placement) onto a particular surface.

The increase in head pitch angle downward when the lower visual field was blocked may have been caused, in part, from the shorter step length observed for both age groups. Furthermore, the larger head pitch angle in the normal vision condition in the older adults may also be explained by the shorter step length for these individuals compared to the young adults. Indeed, step length and mean and maximum head pitch angle are negatively correlated ($r = -0.51$, $P < 0.0001$ and $r = -0.46$, $P < 0.0001$, respectively). Therefore, if one assumes that people fixate approximately two steps ahead while walking on the multi-surface terrain (Marigold and Patla 2007), then by taking shorter steps the head would naturally pitch downward to a greater extent. The increase in trunk pitch forward when the lower visual field was blocked could also facilitate obtaining adequate visual information of the ground terrain. Although both an increase in trunk pitch and shorter step length may lead to a larger head pitch downward the fact that individuals do make these changes while walking is certainly suggestive of the importance of visual information from the lower visual field.

Stability is a fundamental concern when negotiating varying ground terrain. Older adults chose a cautious gait strategy (i.e. reduced step length, slower gait speed, and wider step width) to attenuate head and trunk oscillations compared to young adults (see preceding chapter). Gait adaptations were also observed when the lower visual field was blocked to ensure that stability was maintained across the multi-surface terrain. These observations were independent of age suggesting the importance of visual information from this region. There were minimal changes in trunk acceleration RMS between the visual conditions; however, AP and ML head acceleration RMS were reduced in the LVF condition. These results can be explained, in part, by the reduced gait speed when the lower visual field was blocked. However, trunk pitch and roll RMS were increased when the lower visual field was blocked. The results from the stability margin measures suggest that both the young and older adults kept their trunk COM further away from the lead foot at each foot contact on the multi-surface terrain. Finally, step length was decreased in the LVF condition for both age groups. Thus, without critical information regarding lower limb trajectory, foot placement, and the ground terrain immediately in front from peripheral vision of the lower visual field, individuals attempt to optimize stability by adapting their gait pattern.

One of the limitations of the present study was the use of healthy older adults. Older adults with a high-risk for falling, including those with visual problems stemming from glaucoma, age-related maculopathy, or cataracts may demonstrate different results. In addition, older adults who normally wear multi-focal glasses may be able to accommodate the multi-surface terrain to a greater extent while having their lower visual field blocked than older adults who don't wear these types of glasses. This is unlikely though as fall risk is greater in those who wear multi-focal glasses (Lord et al. 2002).

Many activities of daily living require vision from the lower visual field including negotiating curbs and other obstacles, holes in the ground, changes in ground terrain, and stairs. When vision from this region is compromised either from multi-focal glasses or carrying an object in front (such as a laundry basket), fall-risk increases. This may be even more dramatic in older adults, especially given that older adults tend to naturally fixate below eye level when walking and demonstrate a greater range of fixations compared to young adults (Itoh and Fukuda 2002). The influence of carrying a large object in front of the body is certainly evident in the strategies an individual will adopt to accommodate this task. Instinctively, individuals will manipulate the object they are carrying and/or re-position their head in an attempt to view the ground in front, particularly when negotiating stairs. For example, when binocular vision is removed during a step over an obstacle, people compensate with a head turn to the direction of the occluded eye in order to re-direct the visual field and ensure safe foot trajectory over the obstacle (Patla et al. 2002).

In conclusion, visual information from the lower visual field is important for negotiating varying ground terrain in the travel path. Young and older adults adopt a cautious walking strategy to overcome the difficulty brought on by removing vision from this region. This has important implications for people that wear multi-focal glasses on a daily basis while walking and as such, the use of these glasses in older adults already prone to falling is questioned.

# CHAPTER 7 – General discussion

The results of the experiments in this thesis provide us with insights into the role of vision and the effects of aging on negotiating varying ground terrain in the travel path. Furthermore, the knowledge gained from these experiments will be invaluable in improving our understanding of why people may fall when walking in complex environments and will provide a great foundation for future studies examining how individuals traverse unstable ground terrain.

## 7.1 Stability across varying ground terrain: effects of aging and implications

Aging is associated with reduced visual function, muscle weakness, attenuated sensory function, and an increased risk of falls. Age-related differences in stability while walking across the different ground terrain were observed in the present experiments. This is despite the relatively healthy nature of the older adult sample. An interesting observation was the fact that as the difficulty of the task increased the more unstable the older adults became relative to the young adults. Support for this stems from the fact that there were more differences in stability measures when individuals traversed the multi-surface terrain (Chapter 5) compared to the three similar surfaces in a row (Chapter 2). In addition, within the multi-surface terrain condition, stability was more impaired in the cross condition, which required individuals to deviate from a straight path, compared to the column condition. Therefore, this might suggest that the more challenging the walking environment the more likely older adults will fall and possibly injure themselves.

The age-related impairments in stability were most noticeable in the medial-lateral (ML) direction. Controlling ML stability during walking is imperative to ensure safe forward progression: ML instability has been shown to be associated with fall risk (Lord et al. 1999; Maki et al. 1994; Rogers and Mille 2003). Specifically, spontaneous and induced ML sway during standing is increased among older adult fallers compared to non-fallers and ML spontaneous sway was found to be the best predictor of future fall risk in older adults (Maki et al. 1994). Lack of ML stability following standing perturbations in older adults may be related to changes in neuromuscular factors such as reduced hip abductor-adductor torque (Johnson et al. 2004).

ML instability has also been reported with aging during walking (Woledge et al. 2005). For example, older adults demonstrate less smoothness in acceleration of head and trunk movement in the ML direction compared to young adults (Kavanagh et al. 2005). Older adults often fall to the side (DeGoede et al. 2003; Greenspan et al. 1998; Maki and McIlroy 1996; Rogers and Mille 2003) and laterally directed falls substantially increase the risk of hip fracture (Greenspan et al. 1998; Nankaku et al. 2005; Robinovitch et al. 1991). Thus, these results in conjunction with the findings from this thesis indicate the need to direct interventions for reducing fall risk at improving ML balance in particular. Unfortunately this has not been the case as of yet (Rogers and Mille 2003).

Exercise interventions for reducing falls and improving balance and mobility in older adults have proven to be effective (Barnett et al. 2003; Gardner et al. 2000; Liu-Ambrose et al. 2004; Weerdesteyn et al. 2006). Interventions should include a combination of agility, strength, and endurance exercises. Agility type exercise interventions are effective in persons with chronic stroke: balance and mobility show improvements and there is evidence that falls may also be reduced (Marigold et al. 2005). Agility exercises could include rapid stepping, tandem walking, walking on foam, obstacle courses, stepping to targets, and other exercises to challenge functional balance.

Rogers and Mille (2003) have suggested that exercise interventions should include components emphasizing rapid muscle contractions of the hip musculature and induced stepping that result in rapid changes in limb loading for improving ML stability. Weight-shifting exercises would also be beneficial as demonstrated by short term Tai Chi training for example (Gatts and Woollacott 2006). In addition, interventions should include a component of walking on different and challenging types of ground terrain (see section 7.3 below for more details), which has demonstrated benefits (Li et al. 2005; Means et al. 2005; Weerdesteyn et al. 2006). Nonetheless, future studies should find ways to better improve ML stability in those individuals at risk for falls. Additionally, research into the design of mobility aids should investigate whether mobility aids aimed at increasing ML stability would improve balance and reduce the incidence of falls.

Our understanding of stability during locomotion in complex environments would be incomplete without understanding the role of vision in this context. After all, as stated in the introduction vision has evolved to guide our movements through it (Goodale and Humphrey 1998). The following section looks at how vision is utilized when negotiating challenging ground terrain.

## 7.2 Visual control of locomotion across challenging ground terrain

Vision and action are intricately linked. Vision provides critical information regarding upcoming terrain characteristics and warns us of potentially dangerous situations: it is crucial for proactive control of stability. What I will do now is propose a model for understanding the role of vision in negotiating challenging ground terrain based on the findings of the three experiments on vision in this thesis (see Fig. 7.1).

The most detailed visual information obtained from an environment is that information portrayed onto the foveal and parafoveal aspects of the retina. These regions of the retina contain the most photoreceptors and thus can provide the greatest detail of upcoming ground terrain (Findlay and Gilchrist 2003). However, when combined the eccentricity of these aspects is restricted to only 5° of the visual field. When walking on the multi-surface terrain individuals fixate approximately two steps ahead to regions they will eventually step on. There is the assumption that these individuals are attending to the location of fixation (i.e. overt attention). While this may be true the majority of the time, the need to pitch the head downward to a greater extent when this region is occluded suggests that peripheral vision from the lower visual field is obviously important for safely negotiating the terrain. Therefore, it is highly possible that individuals rapidly switch between overtly attending to the location of gaze fixation for gathering detailed information to use on-line for targeting specific areas to step and covertly (or in extreme cases overtly) attending to the lower visual field to monitor lower limb trajectory and the immediate step when the peripheral visual field contains critical information about the environment. Peripheral visual information is certainly capable of providing critical information about the environment (Marigold et al. 2007; Patla 1998; Rietdyk and Rhea 2006).

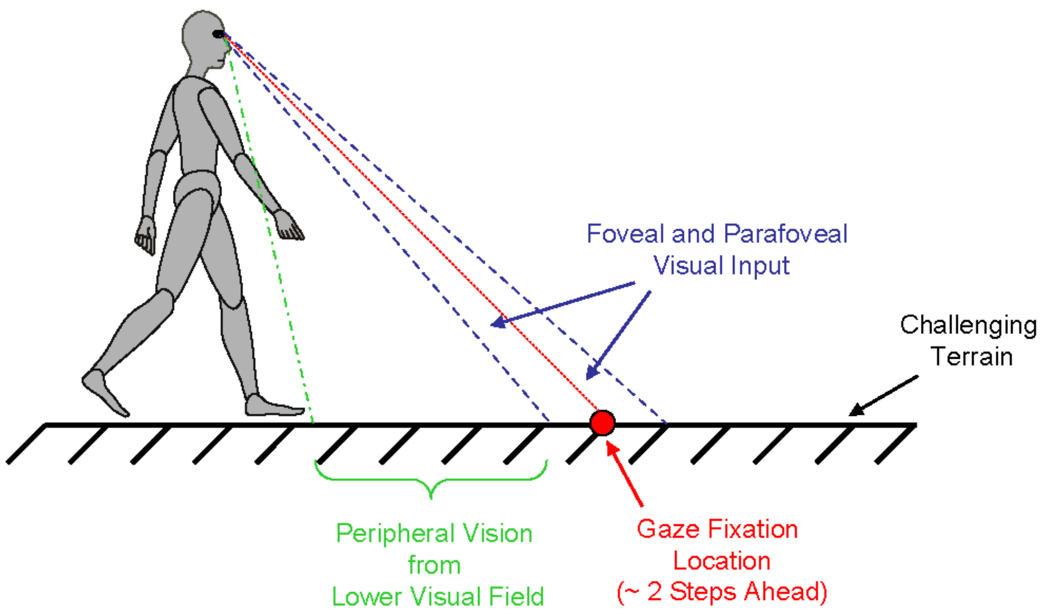



**Figure 7.1:** Role of vision for negotiating challenging ground terrain. Individuals fixate approximately two steps ahead when walking across the multi-surface terrain while also utilizing visual information from the lower visual field.

I hypothesize that individuals spend most of their time overtly attending to the location of fixation approximately two steps ahead with occasional covert shifts of attention to the lower visual field. This overt attention may be a reflection of the dorsal frontoparietal attention network described by Corbetta and Shulman (2002). The dorsal frontoparietal network includes the intraparietal cortex and superior frontal cortex (including the frontal eye fields). This network is involved in preparing (or anticipating) and applying goal directed (top-down) selection for stimuli and responses (Corbetta and Shulman 2002; Corbetta et al. 2000) such as choosing which terrain to step on and establishing a path to take. Our gaze fixation patterns suggest a degree of top-down control as evident from fixations clustered to the columns individuals were restricted to start along for the multi-surface terrain section. Additional support for top-down control of fixation patterns stems from the work of Yarbus (1967), who demonstrated that task instruction modifies the fixation patterns when viewing paintings. Overlapping with the dorsal frontoparietal attention network is the dorsal visual stream. As mentioned, the dorsal visual stream is involved in goal-directed action (Milner and Goodale 1995). This visual processing stream would be used to guide foot placement onto specific surfaces of the multi-surface terrain.

The control of voluntary overt attention by the dorsal frontoparietal attention network is also modulated by detection of salient information from bottom-up processes. It has been suggested that the salience of objects in the environment can be used to create a map to direct eye movements (Corbetta and Shulman 2002) due to the relation of this attention network to the frontal eye field and lateral intraparietal cortex (Colby and Goldberg 1999; Findlay and Gilchrist 2003; Gottlieb et al. 1998; Schall and Hanes 1998; Schall 2002).

How then would visual information from the lower visual field be detected and used in our task? Corbetta and Shulman (2002) have argued that a ventral frontoparietal attention network (predominantly lateralized to the right hemisphere) is involved in the detection of behaviourally relevant (or salient) stimuli (Corbetta and Shulman 2002; Corbetta et al. 2000; Kincade et al. 2005). This network, which works through bottom-up processes, includes the temporoparietal cortex and inferior frontal cortex. This network coincides with the ventral visual processing stream, which has been argued to be involved in object recognition (Milner and Goodale 1995); in this case, identifying the particular surfaces of the multi-surface terrain configurations. The ventral frontoparietal network may act as a circuit breaker or alerting system when a salient stimulus is detected and thus allows for a shift in attention (Astafiev et al. 2006; Corbetta and Shulman 2002; Shulman et al. 2002). This shift in attention results in greater processing of visual information in the lower visual field at the expense of that previously being overtly attended two steps in front and in extreme cases can result in a overt shift to objects (or terrain) in the lower visual field. Thus, I would hypothesize that when a salient stimulus (i.e. a particularly challenging section of ground terrain) is identified by ventral visual stream processing, the ventral frontoparietal network alerts the dorsal frontoparietal attention system and causes a shift of visual attention to that region of the visual field (i.e. lower visual field) so that the terrain can be safely negotiated. This shift can occur either through an overt shift of gaze or covert shift of attention depending upon the perceived danger of that terrain (represented by its salience). Subsequently, the dorsal frontoparietal attention network is engaged and the dorsal visual processing stream is used to guide action. Interestingly, there is ample evidence to suggest that the lower visual field is linked to the dorsal visual processing stream (Brown et al. 2005; Lakha and Humphreys 2005).

Regardless of why visual information from the lower visual field is important for negotiating the varying ground terrain, the fact remains that our results suggest that it might be. This has substantial implications for those who wear multi-focal glasses while walking in challenging environments. As mentioned in the preceding chapter, fall risk is significantly increased among older adults who wear these types of glasses (Lord et al. 2002). While vision from the lower visual field is not occluded when wearing multi-focal glasses, distant (i.e. ground level) visual information obtained when viewing the world through the lower portion of the glasses is distorted (or blurred), which makes it difficult to judge terrain characteristics. There is evidence that light scattering lenses can make walking down a flight of stairs difficult (Buckley et al. 2005a,b; Heasley et al. 2005).

Given the fact that several studies have shown the importance of visual information from the lower visual field and the known fall risk associated with older adults who wear multi-focal glasses, I would strongly recommend the following. First, further research on how multi-focal glasses influence stability when walking in complex environments is needed. Second, I would strongly caution older adults from wearing these types of glasses in situations which require precise foot placement and/or complex environments similar to the multi-surface terrain used in this thesis.

### 7.3 Future directions

There are a whole range of experiments that could be performed using the multi-surface paradigm both from questions that have arisen from the results of the experiments in this thesis and as a follow-up to better understand this paradigm. I will briefly discuss a few potential future studies now but I must stress that this is only the beginning.

While the results demonstrate impairments in stability for the older adults, our sample consisted of relatively healthy individuals. This of course is part of the recruitment processes; it is easier to recruit healthy older adults and these are the individuals most likely to respond to advertisements, etc. However, it will be important to determine how frail older adults and those at higher risk for falls would cope with walking on the multi-surface terrain. In addition, it would be interesting to test individuals with neurological impairments including stroke and Parkinson's disease in this paradigm as both populations are at a high risk for falls and experience various mobility problems. Thus, future work should address these populations in order to further understand potential fall mechanisms and facilitate rehabilitation programs and exercise interventions for those at risk of falling.

Along these lines, the multi-surface terrain paradigm would be extremely useful for investigating the effectiveness of clinical interventions aimed at improving balance and mobility and fall prevention. Importantly, the experiments in this thesis mark the first attempt to understand how young and older individuals walk on varying ground terrain in terms of stability. Thus, this paradigm could act as an outcome measure. Indeed, Means and colleagues (Means 1996; Means et al. 1996a,b; Means and O'Sullivan 2000; Means et al. 1998a,b) have developed an obstacle course using different types of terrain and environmental challenges. The different terrain included sand, carpet, artificial turf, and pine bark chips while the environmental challenges consisted of stairs, ramps, and obstacles. Means et al. (2005) have shown that an exercise program focusing on balance, coordination, and strength training leads to significantly better performance on the obstacle course and reduced prospective falls in the community.

Alternatively, an intervention could entail repetitive training of walking on the multi-surface terrain or a form of it. Li et al. (2005) have shown that walking on a cobblestone mat improves physical function. In addition, using an obstacles course featuring uneven terrain and other different ground surfaces in addition to obstacles and challenges to foot placement, Weerdesteyn et al. (2006) have found a reduced incidence of falling in older adults.

As a follow-up to the experiments on vision it would be important to investigate the role of the other sensory systems such as the somatosensory and vestibular systems in negotiating the multi-surface terrain. This might entail using galvanic vestibular stimulation during the task to probe the vestibular contribution or reducing cutaneous mechanoreceptor information from the plantar surface of the foot to probe the role of pressure sensation from this region. Vestibular information is certainly utilized while walking (Bent et al. 2004) as is information from the sole of the foot (Perry et al. 2001).

While we are able to make statements regarding stability across the entire multi-surface terrain, it is unclear how stepping on a particular surface influences the subsequent step on a different surface or how the following step influences the current step. Thus, future studies should address this by manipulating the order of the different types of surfaces. Only then will we be able to fully understand this paradigm.

Finally, studies on attention and walking on challenging ground terrain may prove to be valuable. By this I mean using a dual-task paradigm while negotiating the multi-surface terrain. An example of this would be having the participants walking and talking at the same time or having participants search for something in the laboratory (analogous to trying to find a particular store while walking along a sidewalk). There is evidence that older adults have difficulty switching attention (Maki et al. 2001) and this may result in a greater risk of falling if individuals do not pay attention to a particularly challenging section of terrain.

### 7.4 Concluding remarks

In conclusion, several key findings have emerged from the experiments of this thesis. First, ML stability is impaired in older adults compared to young adults when walking across challenging ground terrain despite the cautious gait strategy observed in these individuals. Second, individuals fixate highly task-relevant features of the ground terrain in an on-line manner of which this pattern is unaffected by age. And finally, visual information from the lower visual field is important for safely negotiating challenging ground terrain. This latter finding is also independent of age.

## CHAPTER 8 – References


Adkin AL, Frank JS, Carpenter MG, Peysar GW. Fear of falling modifies anticipatory postural control. Exp Brain Res 2002; 143: 160-170.

Aivar MP, Hayhoe MM, Chizk CL, Mruczek REB. Spatial memory and saccadic targeting in a natural task. J Vis 2005; 5: 177-193.

Alexander NB, Ashton-Miller JA, Giordani B, Guire K, Schultz AB. Age differences in timed accurate stepping with increased cognitive and visual demand: a walking trail making test. J Geront A Biol Sci Med Sci 2005; 60A: 1558-1562.

Astafiev SV, Shulman GL, Corbetta M. Visuospatial reorienting signals in the human temporo-parietal junction are independent of response selection. Eur J Neurosci 2006; 23: 591-596.

Ballard DH, Hayhoe MM, Li F, Whitehead SD. Hand-eye coordination during sequential tasks. Philos Trans Proc R Soc Lond B Biol Sci 1992; 337: 331-339.

Barnett A, Smith B, Lord SR, Williams M, Baumand A. Community-based group exercise improves balance and reduces falls in at-risk older people: a randomised controlled trial. Age Ageing 2003; 32: 407-414.

Beloozerova IN, Sirota MG. Integration of motor and visual information in the parietal area 5 during locomotion. J Neurophysiol 2003; 90: 961-971.

Bent LR, Inglis JT, McFadyen BJ. When is vestibular information important during walking? J Neurophysiol 2004; 92: 1269-1275.

Berg WP, Alessio HM, Mills EM, Tong C. Circumstances and consequences of falls in independent community-dwelling older adults. Age Ageing 1997; 26: 261-268.

Bhatt T, Wang E, Pai Y-C. Retention of adaptive control over varying intervals: prevention of slip-induced backward balance loss during gait. J Neurophysiol 2006b; 95: 2913-2922.

Bhatt T, Wening JD, Pai Y-C. Adaptive control of gait stability in reducing slip-related backward loss of balance. Exp Brain Res 2006a; 170: 61-73.

Bhatt T, Wening JD, Pai Y-C. Influence of gait speed on stability: recovery from anterior slips and compensatory stepping. Gait Posture 2005; 21: 146-156.

Black A, Wood J. Vision and falls. Clin Exp Optom 2005; 88: 212-222.

Blake AJ, Morgan K, Bendall MJ, Dallosso H, Ebrahim SB, Arie TH, Fentem PH, Bassey EJ. Falls by elderly people at home: prevalence and associated factors. Age Ageing 1988; 17: 365-372.

Brady RA, Pavol MJ, Owings TM, Grabiner MD. Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. J Biomech 2000; 33: 803-808.

Bremmer F, Duhamel J-R, Ben Hamed S, Graf W. Heading encoding in the macaque ventral intraparietal area (VIP). Eur J Neurosci 2002; 16: 1554-1568.

Broman AT, West SK, Munoz B, Bandeen-Rochie K, Rubin GS, Turano KA. Divided visual attention as a predictor of bumping while walking: the Salisbury Eye Evaluation. Invest Ophthalmol Vis Sci 2004; 45: 2955-2960.

Brown LA, Gage WH, Polych MA, Sleik RJ, Winder TR. Central set influences on gait: age-dependent effects of postural threat. Exp Brain Res 2002; 145: 286-296.

Brown LE, Halpert BA, Goodale MA. Peripheral vision for perception and action. Exp Brain Res 2005; 165: 97-106.

Buckley JG, Heasley K, Scally A, Elliott DB. The effects of blurring vision on medio-lateral balance during stepping up or down to a new level in the elderly. Gait Posture 2005a; 22: 146-153.

Buckley JG, Heasley KJ, Twigg P, Elliott DB. The effects of blurred vision on the mechanics of landing during stepping down by the elderly. Gait Posture 2005b; 21: 65-71.

Campbell AJ, Robertson MC, Gardner MM, Norton RN, Buchner DM. Falls prevention over 2 years: a randomized controlled trial in women 80 years and older. Age Aging 1999; 28: 513-518.

Carpenter MG, Frank JS, Silcher CP. Suface height effects on postural control: a hypothesis for a stiffness strategy for stance. J Vestib Res 1999; 9: 277-286.

Carpenter MG, Frank JS, Silcher GP, Peysar GW. The influence of postural threat on the control of upright stance. Exp Brain Res 2001; 138: 210-218.

Cham R, Redfern MS. Changes in gait when anticipating slippery floors. Gait Posture 2002; 15: 159-171.

Cham R, Redfern MS. Lower extremity corrective reactions to slip events. J Biomech 2001; 34: 1439-1445.

Chambers AJ, Cham R. Slip-related muscle activation patterns in the stance leg during walking. Gait Posture 2006: DOI: 10.1016/j.gaitpost.2006.06.007.

Chapman GJ, Hollands MA. Age-related differences in stepping performance during step cycle-related removal of vision. Exp Brain Res 2006: DOI 10.1007/s00221-006-0507-6.

Chapman GJ, Hollands MA. Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. Gait Posture 2005: doi:10.1016/j.gaitpost.2005.10.002.

Charness N, Reingold EM, Pomplun M, Stampe DM. The perceptual aspect of skilled performance in chess: evidence from eye movements. Mem Cognit 2001; 29: 1146-1152.

Colby CL, Goldberg ME. Space and attention in parietal cortex. Ann Rev Neurosci 1999; 22: 319-349.

Coleman Al, Stone K, Ewing SK, Nevitt M, Cummings S, Cauley JA, Ensrud KE, Harris EL, Hochberg MC, Mangione CM. Higher risk of multiple falls among elderly women who lose visual acuity. Ophthalmology 2004; 111: 857-862.

Corbetta M, Kincade JM, Ollinger JM, McAvoy MP, Shulman GL. Voluntary orienting is dissociated from target detection in human posterior parietal cortex. Nat Neurosci 2000; 3: 292-297.

Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci 2002; 3: 201-215.

Courtine G, Schieppati M. Human walking along a curved path. I. Body trajectory, segment orientation and the effect of vision. Eur J Neurosci 2003; 18: 177-190.

Daley MJ, Spinks WL. Exercise, mobility and aging. Sports Med 2000; 29: 1-12.

Danckert J, Goodale MA. Superior performance for visually guided pointing in the lower visual field. Exp Brain Res 2001; 137: 303-308.

DeGoede KM, Ashton-Miller JA, Schultz AB. Fall-related upper body injuries in the older adult: a review of the biomechanical issues. J Biomech 2003; 36: 1043-1053.

Di Fabio RP, Greany JF, Zampieri C. Saccade-stepping interactions revise the motor plan for obstacle avoidance. J Mot Behav 2003a; 35: 383-397.

Di Fabio RP, Zampieri C, Greany JF. Aging and saccade-stepping interactions in humans. Neurosci Lett 2003b; 339: 179-182.

Di Fabio RP, Zampieri C, Henke J, Olson K, Rickheim D, Russell M. Influence of elderly executive cognitive function on attention in the lower visual field during step initiation. Gerontology 2005; 51: 94-107.

Eng JJ, Winer DA, Patla AE. Strategies for recovery from a trip in early and late swing during human walking. Exp Brain Res 1994; 102: 339-349.

Fajen BR, Warren WH. Behavioral dynamics of steering, obstacle avoidance, and route selection. J Exp Psychol Hum Percept Perform 2003; 29: 343-362.

Ferber R, Ostering LR, Woollacott MH, Wasielewski NJ, Lee J-H. Reactive balance adjustments to unexpected perturbations during human walking. Gait Posture 2002; 16: 238-248.

Findlay JM, Gilchrist ID. Active vision: the psychology of looking and seeing. New York: Oxford University Press, 2003.

Foo P, Warren WH, Duchon A, Tarr MJ. Do humans integrate routes into a cognitive map? Map- versus landmark-based navigation of novel shortcuts. J Exp Psychol Learn Mem Cogn 2005; 31: 195-215.

Forner Cordero A, Koopman HJ, van der Helm FC. Energy analysis of human stumbling: the limitations of recovery. Gait Posture 2005; 21: 243-254.

Fowler GA, Sherk H. Gaze during visually-guided locomotion in cats. Behav Brain Res 2003; 139: 83-96.

Gabel SF, Misslisch H, Schaafsma SJ, Duysens J. Temporal properties of optic flow responses in the ventral intraparietal area. Vis Neurosci 2002; 19: 381-388.

Gardner MM, Robertson MC, Campbell AJ. Exercise in preventing falls and fall related injuries in older people: a review of randomised controlled trials. Br J Sports Med 2000; 34: 7-17.

Gatts SK, Woollacott MH. Neural mechanisms underlying balance improvement with short term Tai Chi training. Aging Clin Exp Res 2006; 18: 7-19.

Geruschat DR, Hassan SE, Turano KA. Gaze behavior while crossing complex intersections. Optom Vis Sci 2003; 80: 515-528.

Geruschat DR, Turano KA, Stahl JW. Traditional measures of mobility performance and retinitis pigmentosa. Optom Vis Sci 1998; 75: 525-537.

Gibson JJ. Perception of the visual world. Boston: Houghton-Mifflin, 1950.

Goldberg ME. The control of gaze. In: Kandel ER, Schwartz JH, Jessell TM (eds). Principles of neural science, fourth edition. New York: McGraw-Hill, 2000, pp. 782-800.

Goodale MA, Humphrey GK. The objects of action and perception. Cognition 1998; 67: 181-207.

Gottlieb JP, Kusunoki M, Goldberg ME. The representation of visual salience in monkey parietal cortex. Nature 1998; 391: 481-484.

Greenspan SL, Myers ER, Kiel DP, Parker RA, Hayes WC, Resnick NM. Fall direction, bone mineral density, and function: risk factors for hip fracture in frail nursing home elderly. Am J Med 1998; 104: 539-545.

Haegerstrom-Portnoy G, Schneck ME, Brabyn JA. Seeing into old age: vision function beyond acuity. Optom Vis Sci 1999; 76: 141-158.

Harwood RH. Visual problems and falls. Age Ageing 2001; 30-S4: 13-18.

Hassan SE, Geruschat DR, Turano KA. Head movements while crossing streets: effect of vision impairment. Optom Vis Sci 2005; 82: 18-26.

Hayhoe M. Vision using routines: a functional account of vision. Vis Cogn 2000; 7: 43-64.

Hayhoe M, Ballard D. Eye movements in natural behavior. Trends Cogn Sci 2005; 9: 188-194.

Hayhoe MM, Lachter J, Feldman J. Integration of form across saccadic eye movements. Perception 1991; 20: 393-402.

Hayhoe MM, Shrivastava A, Mruczek R, Pelz JB. Visual memory and motor planning in a natural task. J Vis 2003; 49-63.

Heasley K, Buckley JG, Scally A, Twigg P, Elliot DB. Falls in older people: effects of age and blurring vision on the dynamics of stepping. Invest Ophthalmol Vis Sci 2005; 46: 3584-3588.

Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. Gait Posture 2006; 24: 237-246.

Helbostad JL, Moe-Nilssen R. The effect of gait speed on lateral balance control during walking in healthy elderly. Gait Posture 2003; 18: 27-36.

Hollands MA, Marple-Horvat DE. Coordination of eye and leg movements during visually guided stepping. J Mot Behav 2001; 33: 205-216.

Hollands MA, Marple-Horvat DE. Visually guided stepping under conditions of step cycle-related denial of visual information. Exp Brain Res 1996; 109: 343-356.

Hollands MA, Marple-Horvat DE, Henkes S, Rowan AK. Human eye movements during visually guided stepping. J Mot Behav 1995; 27: 155-163.

Hollands MA, Patla AE, Vickers JN. "Look where you're going!": gaze behaviour associated with maintaining and challenging the direction of locomotion. Exp Brain Res 2002; 143: 221-230.

Imai T, Moore ST, Raphan T, Cohen B. Interaction of the body, head, and eyes during walking and turning. Exp Brain Res 2001; 136: 1-18.

Itoh N, Fukuda T. Comparative study of eye movements in extent of central and peripheral vision and use by young and elderly walkers. Percept Mot Skills 2002; 94: 1283-1291.

Joffe KM, Scialfa CT. Texture segmentation as a function of eccentricity, spatial frequency and target size. Spat Vis 1995; 9: 325-342.

Johansson RS, Westling G, Bäckström A, Flanagan JR. Eye-hand coordination in object manipulation. J Neurosci 2001; 21: 6917-6932.

Johnson ME, Mille ML, Martinez KM, Crombie G, Rogers MW. Age-related changes in hip abductor and adductor joint torques. Arch Phys Med Rehabil 2004; 85: 593-597.

Kandel ER, Wurtz RH. Constructing the visual image. In: Kandel ER, Schwartz JH, Jessell TM (eds). Principles of neural science, fourth edition. New York: McGraw-Hill, 2000, pp. 492-506.

Kastner S, De Weerd P, Ungerleider LG. Texture segregation in the human visual cortex: a functional MRI study. J Neurophysiol 2000; 83: 2453-2457.

Kavanagh JJ, Barrett RS, Morrison S. Age-related differences in head and trunk coordination during walking. Hum Mov Sci 2005; 24: 574-587.

Kemoun G, Thoumie P, Boisson D, Guieu, JD. Ankle dorsiflexion delay can predict falls in the elderly. J Rehabil Med 2002; 34: 278-283.

Khan MA, Lawrence GP. Differences in visuomotor control between the upper and lower visual fields. Exp Brain Res 2005; 164: 395-398.

Kincade JM, Abrams RA, Astafiev SV, Shulman GL, Corbetta M. An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. J Neurosci 2005; 25: 4593-4604.

Krigolson O, Heath M. A lower visual field advantage for endpoint stability but no advantage for online movement precision. Exp Brain Res 2006; 170: 127-135.

Lakha L, Humphreys G. Lower visual field advantage for motion segmentation during high competition for selection. Spat Vis 2005; 18: 447-460.

Lamme VAF, Rodriguez-Rodriguez V, Spekreijse H. Separate processing dynamics for texture elements, boundaries and surfaces in primary visual cortex of the Macaque monkey. Cereb Cortex 1999; 9: 406-413.

Land MF. Eye movements and the control of actions in everyday life. Prog Retin Eye Res 2006; 25: 296-324.

Land MF. Predictable eye-hand coordination during driving. Nature 1992; 359: 318-320.

Land MF, Hayhoe M. In what ways do eye movements contribute to everyday activities? Vis Res 2001; 41: 3559-3565.

Land MF, Horwood J. Which parts of the road guide steering? Nature 1995; 377: 339-340.

Land MF, Lee DN. Where we look when we steer. Nature 1994; 369: 742-744.

Land MF, McLeod P. From eye movements to actions: how batsmen hit the ball. Nat Neurosci 2000; 3: 1340-1345.

Land M, Mennie N, Rusted J. The roles of vision and eye movements in the control of activities of daily living. Perception 1999; 28: 1311-1328.

Land MF, Tatler BW. Steering with the head: the visual strategy of a racing driver. Curr Biol 2001; 11: 1215-1220.

Lee TS, Mumford D, Romero R, Lamme VAF. The role of the primary visual cortex in higher level vision. Vis Res 1998; 38: 2429-2454.

Li F, Fisher KJ, Harmer P. Improving physical function and blood pressure in older adults through cobblestone mat walking: a randomized trial. J Am Geriatr Soc 2005; 53: 1305-1312.

Liu-Ambrose T, Khan KM, Eng JJ, Janssen PA, Lord SR, McKay HA. Resistance and agility training reduce fall risk in women aged 75-85 with low bone mass: a 6-month randomized, controlled trial. J Am Geriatr Soc 2004; 52: 657-665.

Llewellyn M, Yang JF, Prochazka A. Human H-reflexes are smaller in difficult beam walking than in normal treadmill walking. Exp Brain Res 1990; 83: 22-28.

Lockhart TE, Woldstad JC, Smith JL. Effects of age-related gait changes on the biomechanics of slips and falls. Ergonomics 2003; 46: 1136-1160.

Lockhart TE, Woldstad JC, Smith JL, Ramsey JD. Effects of age related sensory degradation on perception of floor slipperiness and associated slip parameters. Safety Sci 2002; 40: 689-703.

Lord SR. Visual risk factors for falls in older people. Age Ageing 2006; 35-S2: ii42-ii45.

Lord SR, Dayhew J. Visual risk factors for falls in older people. J Am Geriatr Soc 2001; 49: 508-515.

Lord SR, Dayhew J, Howland A. Multifocal glasses impair edge-contrast sensitivity and depth perception and increase the risk of falls in older people. J Am Geriatr Soc 2002; 50: 1760-1766.

Lord SR, Menz HB. Visual contribution to postural stability in older adults. Gerontology 2000; 46: 306-310.

Lord SR, Rogers MW, Howland A, Fitzpatrick RC. Lateral stability, sensorimotor function and falls in older people. J Am Geriatr Soc 1999; 47: 1077-1081.

Mackey DC, Robinovitch SN. Mechanisms underlying age-related differences in ability to recover balance with the ankle strategy. Gait Posture 2006; 23: 59-68.

MacLellan MJ, Patla AE. Adaptations of walking pattern on a compliant surface to regulate dynamic stability. Exp Brain Res 2006a; 173: 521-530.

MacLellan MJ, Patla AE. Stepping over an obstacle on a compliant travel surface reveals adaptive and maladaptive changes in locomotion patterns. Exp Brain Res 2006b; 173: 531-538.

Maki BE, Edmondstone MA, McIlory WE. Age-related differences in laterally directed compensatory stepping behavior. J Gerontol A Biol Sci Med Sci 2000; 55A: M270-M277.

Maki BE, Holliday PJ, Topper AK. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. J Gerontol A Biol Sci Med Sci 1994; 49: M72-M84.

Maki BE, McIlory WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. Age Ageing 2006; 35: ii12-ii18.

Maki BE, McIlory WE. The role of limb movements in maintaining upright stance: the “change-in-support” strategy. Phys Ther 1997; 77: 488-507.

Maki BE, McIlroy WE. Postural control in the older adult. Clin Geriatr Med 1996; 12: 635-658.

Maki BE, Zecevic A, Bateni H, Kirshebaum N, McIlroy WE. Cognitive demands of executing postural reactions: does aging impede attention switching? NeuroReport 2001; 12: 3583-3587.

Marigold DS, Bethune AJ, Patla AE. Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. J Neurophysiol 2003; 89: 1727-1737.

Marigold DS, Eng JJ, Dawson AS, Inglis JT, Harris JE, Gylfadottir S. Exercise leads to faster postural reflexes, improved balance and mobility, and fewer falls in older persons with chronic stroke. J Am Geriatr Soc 2005; 53: 416-423.

Marigold DS, Patla AE. Gaze fixation patterns for negotiating complex ground terrain. Neuroscience 2007; 144: 302-313.

Marigold DS, Patla AE. Adapting locomotion to different surface compliances: neuromuscular responses and changes in movement dynamics. J Neurophysiol 2005; 94: 1733-1750.

Marigold DS, Patla AE. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. J Neurophysiol 2002; 88: 339-353.

Marigold DS, Weerdesteyn V, Patla AE, Duysens J. Keep looking ahead? Re-direction of visual fixation does not always occur during an unpredictable obstacle avoidance task. Exp Brain Res 2007; 176: 32-42.

Marple-Horvat DE, Chattington M, Anglesea M, Ashford DG, Wilson M, Keil D. Prevention of coordinated eye movements and steering impairs driving performance. Exp Brain Res 2005; 163: 411-420.

Means KM. The obstacle course: a tool for the assessment of functional balance and mobility in the elderly. J Rehabil Res Dev 1996; 33: 413-428.

Means KM, O'Sullivan PS. Modifying a functional obstacle course to test balance and mobility in the community. J Rehabil Res Dev 2000; 37: 621-632.

Means KM, Rodell DE, O'Sullivan PS. Balance, mobility, and falls among community-dwelling elderly persons: effects of a rehabilitation exercise program. Am J Phys Med Rehabil 2005; 84: 238-250.

Means KM, Rodell DE, O'Sullivan PS. Obstacle course performance and risk of falling in community-dwelling elderly persons. Arch Phys Med Rehabil 1998a; 79: 1570-1576.

Means KM, Rodell DE, O'Sullivan PS. Use of an obstacle course to assess balance and mobility in the elderly: a validation study. Am J Phys Med Rehabil 1996a; 75: 88-95.

Means KM, Rodell DE, O'Sullivan PS, Cranford LA. Rehabilitation of elderly fallers: pilot study of a low to moderate exercise program. Arch Phys Med Rehabil 1996b; 77: 1030-1036.

Means KM, Rodell DE, O'Sullivan PS, Winger RM. Comparison of a functional obstacle course with an index of clinical gait and balance and postural sway. J Gerontol A Biol Sci Med Sci 1998b; 53: M331-M335.

Menz HB, Lord SR, Fitzpatrick RC. Age-related differences in walking stability. Age Ageing 2003a; 32: 137-142.

Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. Gait Posture 2003b; 18: 35-46.

Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking are associated with risk of falling in community-dwelling older people. J Gerontol A Biol Sci Med Sci 2003c; 58A: 446-452.

Mille ML, Johnson ME, Martinez KM, Rogers MW. Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech 2005; 20: 607-616.

Milner AD, Goodale MA. The visual brain in action. New York: Oxford University Press, 1995.

Misiaszek JE. Early activation of arm and leg muscles following pulls to the waist during walking. Exp Brain Res 2003; 151: 318-329.

Misiaszek JE, Krauss EM. Restricting arm use enhances compensatory reactions of leg muscles during walking. Exp Brain Res 2005; 161: 474-485.

Mohagheghi AA, Moraes R, Patla AE. The effects of distant and on-line visual information on the control of approach phase and step over an obstacle during locomotion. Exp Brain Res 2004; 155: 459-468.

Moore T, Armstrong KM, Fallah M. Visuomotor origins of covert spatial attention. Neuron 2003; 40: 671-683.

Mooreland JD, Richardson JA, Goldsmith CH, Clase CM. Muscle weakness and falls in older adults: a systematic review and meta-analysis. J Am Geriatr Soc 2004; 52: 1121-1129.

Munoz DP. Commentary: saccadic eye movements: overview of neural circuitry. Prog Brain Res 2002; 140: 89-96.

Munoz DP, Istvan PJ. Lateral inhibitory interactions in the intermediate layers of the monkey superior colliculus. J Neurophysiol 1998; 79: 1193-1209.

Nankaku M, Kanzaki H, Tsuboyama T, Nakamura T. Evaluation of hip fracture risk in relation to fall direction. Osteoporos Int 2005; 16: 1315-1320.

Nieuwenhuijzen PHJA, Duysens J. Whole body responses after ankle inversions during walking. Gait Posture 2005; 21(suppl. 1): S80.

Nieuwenhuijzen PHJA, Grüneberg C, Duysens J. Mechanically induced ankle inversion during human walking and jumping. J Neurosci Meth 2002; 117: 133-140.

Norton R, Campbell AJ, Lee-Joe T, Robinson E, Butler M. Circumstances of falls resulting in hip fractures among older people. J Am Geriatr Soc 1997; 45: 1108-1112.

Oates AR, Patla AE, Frank JS, Greig MA. Control of dynamic stability during gait termination on a slippery surface. J Neurophysiol 2005; 93: 64-70.

Owsley C, Ball K, Keeton DM. Relationship between visual sensitivity and target localization in older adults. Vis Res 1995; 35: 579-587.

Patel I, Turano KA, Broman AT, Bandeen-Roche K, Munoz B, West SK. Measures of visual function and percentage of preferred walking speed in older adults: The Salisbury Eye Evaluation Project. Invest Ophthalmol Vis Sci 2006; 47: 65-71.

Patla AE. Gaze behaviors during adaptive human locomotion: insights into how vision is used to regulate locomotion. In: Vaina LM, Beardsley SA, Rushton SK (eds). Optic flow and beyond. Dordrecht, Kluwer Academic Publishers, 2004, pp. 383-399.

Patla AE. Strategies for dynamic stability during adaptive human locomotion: contributions of visual, vestibular, and kinesthetic inputs to maintaining balance in complex environments. IEEE Eng Med Biol Mag 2003; 22: 48-52.

Patla AE. How is human gait controlled by vision? Ecological Psychology 1998; 10: 287-302.

Patla AE. Understanding the roles of vision in the control of human locomotion. Gait Posture 1997; 5: 54-69.

Patla AE, Adkin A, Martin C, Holden R, Prentice S. Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. Exp Brain Res 1996; 112: 513-522.

Patla AE, Goodale MA. Obstacle avoidance during locomotion is unaffected in a patient with visual form agnosia. Neuroreport 1996; 8: 165-168.

Patla AE, Greig MA. Any way you look at it, successful obstacle negotiation needs visually guided on-line foot placement regulation during the approach phase. Neurosci Lett 2006; 397: 110-114.

Patla AE, Niechwiej E, Racco V, Goodale MA. Understanding the contribution of binocular vision to the control of adaptive locomotion. Exp Brain Res 2002; 142: 551-561.

Patla AE, Prentice S, Robinson C, Neufield J. Visual control of locomotion: strategies for changing direction and for going over obstacles. J Exp Psychol Hum Percept Perform 1991; 17: 603-634.

Patla AE, Robinson C, Samways M, Armstrong CJ. Visual control of step length during overground locomotion: task-specific modulation of the locomotion synergy. J Exp Psychol Hum Percept Perform 1989; 25: 603-617.

Patla AE, Vickers JN. How far ahead do we look when required to step on specific locations in the travel path during locomotion? Exp Brain Res 2003; 148: 133-138.

Patla AE, Vickers JN. Where and when do we look as we approach and step over an obstacle in the travel path? Neuroreport 1997; 8: 3661-3665.

Pavol MJ, Owings TM, Foley KT, Grabiner MG. Mechanisms leading to a fall from an induced trip in healthy older adults. J Gerontol A Biol Sci Med Sci 2001; 56A: M428-M437.

Pelz JB, Canosa R. Oculomotor behavior and perceptual strategies in complex tasks. Vis Res 2001; 41: 3587-3596.

Perry SD. Evaluation of age-related plantar-surface insensitivity and onset age of advanced insensitivity in older adults using vibratory and touch sensation tests. Neurosci Lett 2006; 392: 62-67.

Perry SD, Santos LC, Patla AE. Contribution of vision and cutaneous sensation to the control of centre of mass (COM) during gait termination. Brain Res 2001; 913: 27-34.

Pierrot-Deseilligny C, Rivaud S, Gaymard B, Agid Y. Cortical control of reflexive visually-guided saccades. Brain 1991; 114: 1473-1485.

Pijnappels M, Bobbert MF, van Dieën JH. Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. Gait Posture 2005a; 21: 388-394.

Pijnappels M, Bobbert MF, van Dieën JH. Control of support limb muscles in recovery after tripping in young and older subjects. Exp Brain Res 2005b; 160: 326-333.

Pijnappels M, Bobbert MF, van Dieën JH. How early reactions in the support limb contribute to balance recovery after tripping. J Biomech 2005c; 38: 627-634.

Pijnappels M, Bobbert MF, van Dieën JH. Contribution of the support limb in control of angular momentum after tripping. J Biomech 2004; 37: 1811-1818.

Podsiadlo D, Richardson S. The timed “up & go”: a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc 1991; 39: 142-148.

Powell L, Myers AM. The activities-specific balance confidence (ABC) scale. J Gerontol A Biol Sci Med Sci 1995; 50A: M28-M34.

Prime SL, Niemeier M, Crawford JD. Transsaccadic integration of visual features in a line intersection task. Exp Brain Res 2006; 169: 532-548.

Prince F, Corriveau H, Hebert R, Winter DA. Gait in the elderly. Gait Posture 1997; 5: 128-135.

Reingold EM, Charness N, Pomplun M, Stampe DM. Visual span in expert chess players: evidence from eye movements. Psychol Sci 2001; 12: 48-55.

Reynolds RF, Day BL. Visual guidance of the human foot during a step. J Physiol 2005; 569: 577-684.

Richardson JK, Thies SB, DeMott T, Ashton-Miller JA. Gait analysis in a challenging environment differentiates between fallers and nonfallers among older patients with peripheral neuropathy. Arch Phys Med Rehabil 2005; 86: 1539-1544.

Richardson JK, Thies SB, DeMott T, Ashton-Miller JA. A comparison of gait characteristics between older women with and without peripheral neuropathy in standard and challenging environments. J Am Geriatr Soc 2004; 52: 1532-1537.

Rietdyk S, Patla AE. Context-dependent reflex control: some insights into the role of balance. Exp Brain Res 1998; 119: 251-259.

Rietdyk S, Rhea CK. Control of adaptive locomotion: effect of visual obstruction and visual cues in the environment. Exp Brain Res 2006; 169: 272-278.

Robinovitch SN, Hayes WC, McMahon TA. Prediction of femoral impact forces in falls on the hip. J Biomech Eng 1991; 113: 366-374.

Rogers MW, Mille ML. Lateral stability and falls in older people. Exerc Sport Sci Rev 2003; 31: 182-187.

Rossi AF, Desimone R, Ungerleider LG. Contextural modulation in primary visual cortex of macaques. J Neurosci 2001; 21: 1698-1709.

Salthouse TA. The processing-speed theory of adult age differences in cognition. Psychol Rev 1996; 103: 403-428.

Schaafsma SJ, Duysens J. Neurons in the ventral intraparietal area of awake macaque monkey closely resemble neurons in the dorsal part of the medial superior temporal area in their responses to optic flow patterns. J Neurophysiol 1996; 76: 4056-4068.

Schaafsma SJ, Duysens J, Gielen CCAM. Responses in ventral intraparietal area of awake macaque monkey to optic flow patterns corresponding to rotation of planes in depth can be explained by translation and expansion effects. Vis Neurosci 1997; 14: 633-646.

Schall JD. The neural selection and control of saccades by the frontal eye fields. Philos Trans R Soc Lond B Biol Sci 2002; 357: 1073-1082.

Schall JD, Hanes DP. Neural mechanisms of selection and control of visually guided eye movements. Neural Netw 1998; 11: 1241-1251.

Schillings AM, Mulder TH, Duysens J. Stumbling over obstacles in older adults compared to young adults. J Neurophysiol 2005; 94: 1158-1168.

Schillings AM, Van Wezel BMH, Duysens J. Mechanically induced stumbling during human treadmill walking. J Neurosci Meth 1996; 67: 11-17.

Schillings AM, Van Wezel BMH, Mulder TH, Duysens J. Muscular responses and movement strategies during stumbling over obstacles. J Neurophysiol 2000; 83: 2093-2102.

Schillings AM, Van Wezel BMH, Mulder TH, Duysens J. Widespread short-latency stretch reflexes and their modulation during stumbling over obstacles. Brain Res 1999; 816: 480-486.

Schubert M, Bohner C, Berger W, Sprundel M.v., Duysens JEJ. The role of vision in maintaining heading direction: effects of changing gaze and optic flow on human gait. Exp Brain Res 2003; 150: 163-173.

Sekuler AB, Bennett PJ, Mamelak M. Effects of aging on the useful field of view. Exp Aging Res 2000; 26: 103-120.

Sereno MI, Pitzalis S, Martinez A. Mapping of contralateral space in retinotopic coordinates by a parietal cortical area in humans. Science 2001; 294: 1350-1354.

Sherk H, Fowler GA. Visual analysis and image motion in locomoting cats. Eur J Neurosci 2001; 13: 1239-1248.

Shulman GL, Tansy AP, Kincade M, Petersen SE, McAvoy MP, Corbetta M. Reactivation of networks involved in preparatory states. Cereb Cortex 2002; 12: 590-600.

Siegmund GP, Heiden TL, Sanderson DJ, Inglis JT, Brault JR. The effect of subject awareness and prior slip experience on tribometer-based predictions of slip probability. Gait Posture 2006; 24: 110-119.

Sparks DL. Conceptual issues related to the role of the superior colliculus in the control of gaze. Curr Opin Neurobiol 1999; 9: 698-707.

Spaulding SJ, Patla AE, Flanagan J, Elliot DB, Rietdyk S, Brown KS. Waterloo Vision and Mobility Study: normal gait characteristics during dark and light adaptation in individuals with age-related maculopathy. Gait Posture 1995; 3: 227-235.

Tang P-F, Woollacott MH. Phase-dependent modulation of proximal and distal postural responses to slips in young and older adults. J Gerontol A Biol Sci Med Sci 1999; 54A: M89-M102.

Tang P-F, Woollacott MH. Inefficient postural responses to unexpected slips during walking in older adults. J Gerontol A Biol Sci Med Sci 1998; 53A: M471-M480.

Tang P-F, Woollacott MH, Chong RKY. Control of reactive balance adjustments in perturbed human walking: roles of proximal and distal postural muscle activity. Exp Brain Res 1998; 119: 141-152.

Thies SB, Richardson JK, Ashton-Miller JA. Effects of surface irregularity and lighting on step variability during gait: a study in healthy young and older women. Gait Posture 2005a; 22: 26-31.

Thies SB, Richardson JK, DeMott T, Ashton-Miller JA. Influence of an irregular surface and low light on the step variability of patients with peripheral neuropathy during level gait. Gait Posture 2005b; 22: 40-45.

Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. N Engl J Med 1988; 319: 1701-1707.

Tinetti ME, Williams CS. The effect of falls and fall injuries on functioning in community-dwelling older persons. J Gerontol A Biol Sci Med Sci 1998; 53A: M112-M119.

Tombaugh TN. Trail making test A and B: normative data stratified by age and education. Arch Clin Neuropsychol 2004; 19: 203-214.

Turano KA, Broman AT, Bandeen-Rochie K, Munoz B, Rubin GS, West SK, SEE Project Team. Association of visual field loss and mobility performance in older adults: Salisbury eye evaluation study. Optom Vis Sci 2004; 81: 298-307.

Turano KA, Geruschat DR, Baker FH. Oculomotor strategies for the direction of gaze tested with a real-world activity. Vis Res 2003; 43: 333-346.

Turano KA, Yu D, Hao L, Hicks JC. Optic-flow and egocentric-direction strategies in walking: central vs peripheral visual field. Vis Res 2005; 45: 3117-3132.

Triesch J, Ballard DH, Hayhoe MM, Sullivan BT. What you see is what you need. J Vis 2003; 3: 86-94.

Ungerleider LG, Mishkin M. Two cortical visual systems. In: Ingle DJ, Goodale MA, Mansfield RJW (eds). Analysis of visual behavior. Cambridge: MIT Press, 1982, pp. 549-586.

van den Boget AJ, Pavol MJ, Grabiner MD. Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip. J Biomech 2002; 35: 199-205.

von der Heydt R, Zhou H, Friedman HS. Representation of stereoscopic edges in monkey visual cortex. Vis Res 2000; 40: 1955-1967.

Warren WH, Kay BA, Zosh WD, Duchon AP, Sahuc S. Optic flow is used to control human walking. Nat Neurosci 2001; 4: 213-216.

Watson GR. Low vision in the geriatric population: rehabilitation and management. J Am Geriatr Soc 2001; 49: 317-330.

Weerdesteyn V, Nienhuis B, Mulder T, Duysens J. Older women strongly prefer stride lengthening to shortening in avoiding obstacles. Exp Brain Res 2005; 161: 39-46.

Weerdesteyn V, Rijken H, Geurts ACH, Smits-Engelsman BCM, Mulder T, Duysens J. A five-week exercise program can reduce falls and improve obstacle avoidance in the elderly. Gerontology 2006; 52: 131-141.

West CG, Gildengorin G, Haegerstrom-Portnoy G, Schneck ME, Lott L, Brabyn JA. Is vision function related to physical functional ability in older adults? J Am Geriatr Soc 2002; 50: 136-145.

Wilkie RM, Wann JP. Eye-movements aid the control of locomotion. J Vis 2003; 3: 677-684.

Wilkinson EJ, Sherk HA. The use of visual information for planning accurate steps in a cluttered environment. Behav Brain Res 2005; 164: 270-274.

Winter DA. Biomechanics and motor control of human movement, third edition. New Jersey: John Wiley & Sons, Inc., 2005.

Winter DA. The biomechanics and motor control of human gait: normal, elderly and pathological, second edition. Waterloo: Waterloo Biomechanics, 1991.

Woledge RC, Birtles DB, Newham DJ. The variable component of lateral body sway during walking in young and older humans. J Gerontol A Biol Sci Med Sci 2005; 60A: 1463-1468.

Wu B, Ooi TL, He ZJ. Perceiving distance accurately by a directional process of integrating ground information. Nature 2004; 428: 73-77.

Wurtz RH, Kandel ER. Central visual pathways. In: Kandel ER, Schwartz JH, Jessell TM (eds). Principles of neural science, fourth edition. New York: McGraw-Hill, 2000, pp. 523-547.

Yang B-S, Ashton-Miller JA. Stepping onto raised, laterally compliant structures: a biomechanical study of age and gender effects in healthy adults. Human Factors 2006; 48: 207-218.

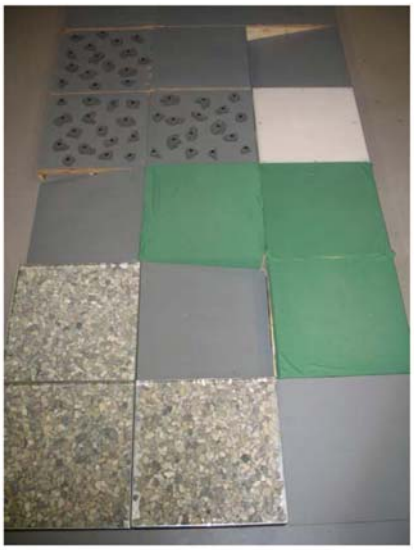
Yarbus A. Eye movements and vision. New York: Plenum Press, 1967.

You J-Y, Chou Y-L, Lin C-J, Su F-C. Effect of slip on movement of body center of mass relative to base of support. Clin Biomech 2001; 16: 167-173.

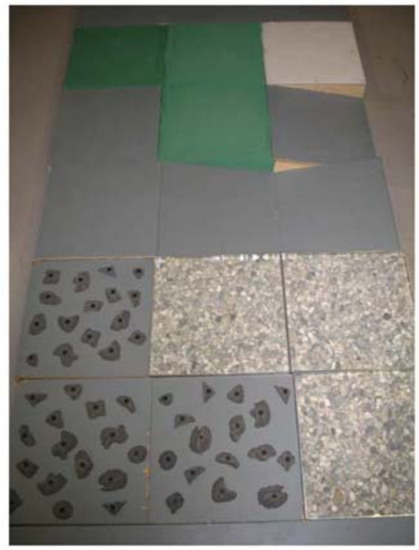
Zhang T, Britten KH. Clustering of selectivity for optic flow in the ventral intraparietal area. NeuroReport 2004; 15: 1941-1945.

**APPENDIX A**

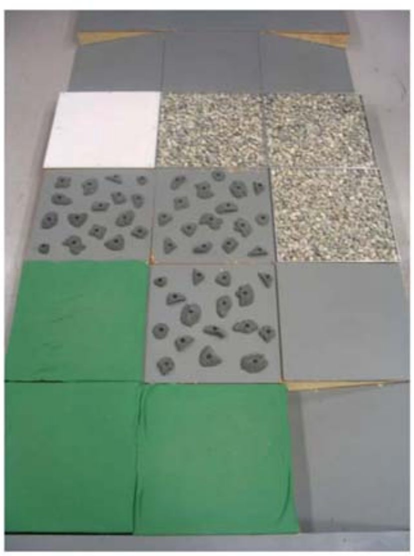
Multi-surface Configuration A



Multi-surface Configuration B



Multi-surface Configuration D



**APPENDIX B**

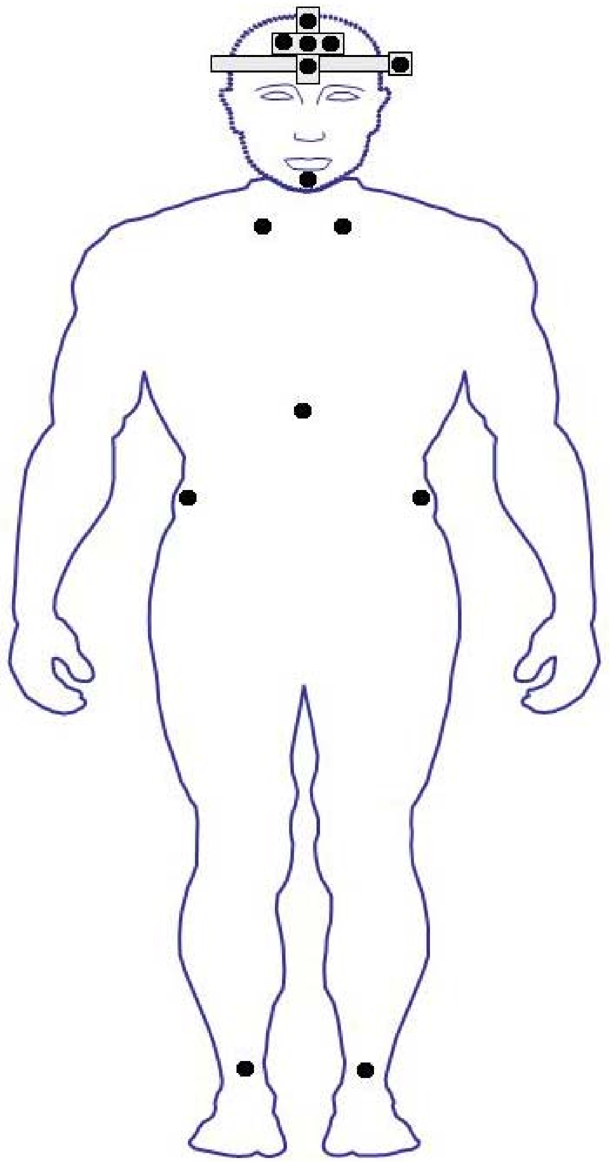
Surface Study Protocol

Date: _________ Subject Code: ________

| # | Configuration | Condition | Trial # |
|---|---|---|---|
| 1 | Control | Control | |
| 2 | Control | Control | |
| 3 | Control | Control | |
| 4 | Middle | Irregular | |
| 5 | Middle | Irregular | |
| 6 | Middle | Irregular | |
| 7 | Middle | ML Tilt - L/R/L | |
| 8 | Middle | ML Tilt - L/R/L | |
| 9 | Middle | ML Tilt - L/R/L | |
| 10 | Middle | Compliant | |
| 11 | Middle | Compliant | |
| 12 | Middle | Compliant | |
| 13 | Edge | Irregular | |
| 14 | Edge | Irregular | |
| 15 | Edge | Irregular | |
| 16 | Edge | Compliant | |
| 17 | Edge | Compliant | |
| 18 | Edge | Compliant | |
| 19 | Edge | ML Tilt - L/R/L | |
| 20 | Edge | ML Tilt - L/R/L | |
| 21 | Edge | ML Tilt - L/R/L | |

**APPENDIX C**

Position Marker Set-up



## APPENDIX D

Young Adult Gaze Protocol

| # | Configuration | Condition | Trial # |
|---|---|---|---|
| 1 | Control | Control | |
| 2 | Control | Control | |
| 3 | Control | Control | |
| 4 | Control | Control | |
| 5 | Config. B | Natural | |
| 6 | Config. B | Start Left | |
| 7 | Config. B | Start Right | |
| 8 | Config. B | Start Centre | |
| 9 | Config. D | Start Right | |
| 10 | Config. D | Start Centre | |
| 11 | Config. D | Natural | |
| 12 | Config. D | Start Left | |
| 13 | Config. A | Start Centre | |
| 14 | Config. A | Start Left | |
| 15 | Config. A | Natural | |
| 16 | Config. A | Start Right | |
| 17 | Config. B | Start Right | |
| 18 | Config. B | Start Centre | |
| 19 | Config. B | Natural | |
| 20 | Config. B | Start Left | |
| 21 | Config. A | Natural | |
| 22 | Config. A | Start Right | |
| 23 | Config. A | Start Left | |
| 24 | Config. A | Start Centre | |
| 25 | Config. D | Start Right | |
| 26 | Config. D | Start Left | |
| 27 | Config. D | Natural | |
| 28 | Config. D | Start Centre | |
| 29 | Config. D | Start Right | |
| 30 | Config. D | Start Centre | |
| 31 | Config. D | Natural | |
| 32 | Config. D | Start Left | |
| 33 | Config. A | Start Right | |
| 34 | Config. A | Start Centre | |
| 35 | Config. A | Natural | |
| 36 | Config. A | Start Left | |
| 37 | Config. B | Start Right | |
| 38 | Config. B | Start Left | |
| 39 | Config. B | Natural | |
| 40 | Config. B | Start Centre | |

Subject Code: ________

Date: _______________

**APPENDIX E**

Older Adult Gaze Protocol

| # | Configuration | Condition | Trial # |
|---|---|---|---|
| 1 | Control | Control | |
| 2 | Control | Control | |
| 3 | Control | Control | |
| 4 | Control | Control | |
| 5 | Config. B | Natural | |
| 6 | Config. B | Start Left | |
| 7 | Config. B | Start Right | |
| 8 | Config. B | Start Centre | |
| 9 | Config. D | Start Right | |
| 10 | Config. D | Start Centre | |
| 11 | Config. D | Natural | |
| 12 | Config. D | Start Left | |
| 13 | Config. A | Start Centre | |
| 14 | Config. A | Start Left | |
| 15 | Config. A | Natural | |
| 16 | Config. A | Start Right | |
| 17 | Config. B | Start Right | |
| 18 | Config. B | Start Centre | |
| 19 | Config. B | Natural | |
| 20 | Config. B | Start Left | |
| 21 | Config. A | Natural | |
| 22 | Config. A | Start Right | |
| 23 | Config. A | Start Left | |
| 24 | Config. A | Start Centre | |
| 25 | Config. D | Start Right | |
| 26 | Config. D | Start Left | |
| 27 | Config. D | Natural | |
| 28 | Config. D | Start Centre | |

Subject Code: _________

Date: ________________

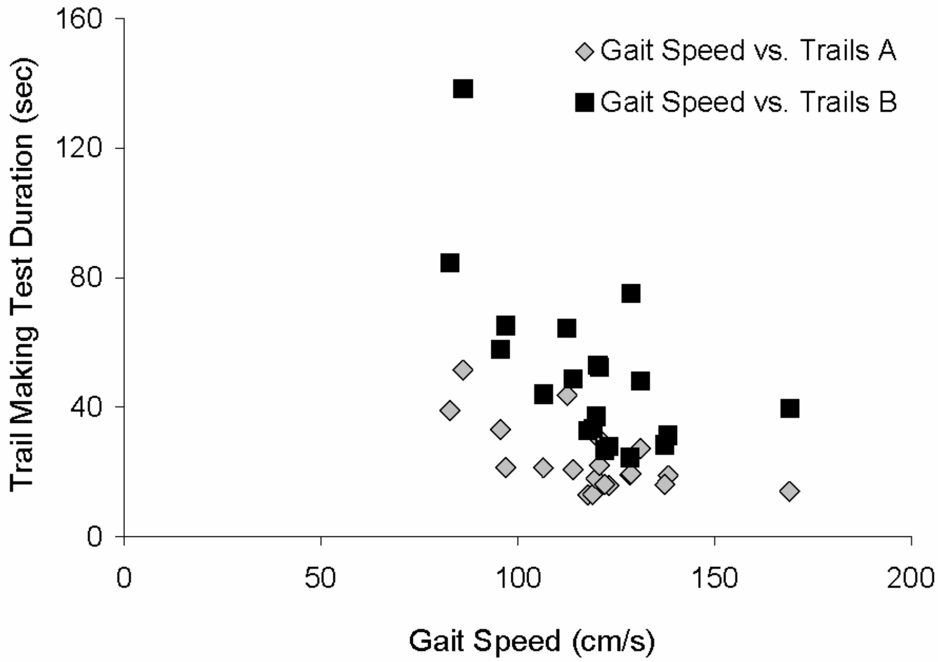
# APPENDIX F

## Multi-surface Protocol

Date: ________ Subject Code: _______

| # | Vision | Configuration | Condition | Trial # | # | Vision | Configuration | Condition | Trial # |
|---|---|---|---|---|---|---|---|---|---|
| 1 | PV Occluded | Control | Control | | 35 | Normal | Config. A | Start Centre - End Centre | |
| 2 | PV Occluded | Control | Control | | 36 | Normal | Config. A | Start Left - End Left | |
| 3 | PV Occluded | Control | Control | | 37 | Normal | Config. A | Start Left - End Right | |
| 4 | PV Occluded | Control | Control | | 38 | Normal | Config. A | Start Right - End Centre | |
| 5 | Normal | Control | Control | | 39 | PV Occluded | Config. A | Natural | |
| 6 | Normal | Control | Control | | 40 | PV Occluded | Config. A | Start Left - End Right | |
| 7 | Normal | Control | Control | | 41 | PV Occluded | Config. A | Start Left - End Left | |
| 8 | Normal | Control | Control | | 42 | PV Occluded | Config. A | Start Right - End Left | |
| 9 | Normal | Config. B | Natural | | 43 | PV Occluded | Config. A | Start Centre - End Left | |
| 10 | Normal | Config. B | Start Left - End Centre | | 44 | PV Occluded | Config. A | Start Centre - End Right | |
| 11 | Normal | Config. B | Start Right - End Left | | 45 | PV Occluded | Config. A | Start Right - End Right | |
| 12 | Normal | Config. B | Start Centre - End Left | | 46 | PV Occluded | Config. A | Start Right - End Centre | |
| 13 | Normal | Config. B | Start Right - End Right | | 47 | PV Occluded | Config. A | Start Left - End Centre | |
| 14 | Normal | Config. B | Start Centre - End Right | | 48 | PV Occluded | Config. A | Start Centre - End Centre | |
| 15 | Normal | Config. B | Start Left - End Left | | 49 | PV Occluded | Config. B | Natural | |
| 16 | Normal | Config. B | Start Centre - End Centre | | 50 | PV Occluded | Config. B | Start Right - End Left | |
| 17 | Normal | Config. B | Start Right - End Centre | | 51 | PV Occluded | Config. B | Start Left - End Right | |
| 18 | Normal | Config. B | Start Left - End Right | | 52 | PV Occluded | Config. B | Start Left - End Left | |
| 19 | Normal | Config. D | Natural | | 53 | PV Occluded | Config. B | Start Right - End Right | |
| 20 | Normal | Config. D | Start Left - End Right | | 54 | PV Occluded | Config. B | Start Left - End Centre | |
| 21 | Normal | Config. D | Start Right - End Right | | 55 | PV Occluded | Config. B | Start Centre - End Left | |
| 22 | Normal | Config. D | Start Centre - End Centre | | 56 | PV Occluded | Config. B | Start Centre - End Right | |
| 23 | Normal | Config. D | Start Right - End Centre | | 57 | PV Occluded | Config. B | Start Right - End Centre | |
| 24 | Normal | Config. D | Start Right - End Left | | 58 | PV Occluded | Config. B | Start Centre - End Centre | |
| 25 | Normal | Config. D | Start Centre - End Left | | 59 | PV Occluded | Config. D | Natural | |
| 26 | Normal | Config. D | Start Left - End Centre | | 60 | PV Occluded | Config. D | Start Left - End Left | |
| 27 | Normal | Config. D | Start Centre - End Right | | 61 | PV Occluded | Config. D | Start Right - End Left | |
| 28 | Normal | Config. D | Start Left - End Left | | 62 | PV Occluded | Config. D | Start Left - End Centre | |
| 29 | Normal | Config. A | Natural | | 63 | PV Occluded | Config. D | Start Left - End Right | |
| 30 | Normal | Config. A | Start Centre - End Right | | 64 | PV Occluded | Config. D | Start Right - End Centre | |
| 31 | Normal | Config. A | Start Right - End Right | | 65 | PV Occluded | Config. D | Start Centre - End Centre | |
| 32 | Normal | Config. A | Start Centre - End Left | | 66 | PV Occluded | Config. D | Start Centre - End Left | |
| 33 | Normal | Config. A | Start Left - End Centre | | 67 | PV Occluded | Config. D | Start Right - End Right | |
| 34 | Normal | Config. A | Start Right - End Left | | 68 | PV Occluded | Config. D | Start Centre - End Right | |

**APPENDIX G**




Gait Speed vs. Trails A → r = -0.64, P = 0.003

Gait Speed vs. Trails B → r = -0.62, P = 0.004

**APPENDIX H**

Glasses that block the lower visual field (i.e. LVF condition)