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Failures in adaptive locomotion in healthy young adults

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Approved by: Dr. David B. Klenosky 4/27/2016
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FAILURES IN ADAPTIVE LOCOMOTION IN HEALTHY YOUNG ADULTS

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Michel J.H. Heijnen

In Partial Fulfillment of the

Requirements for the Degree

of

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West Lafayette, Indiana

For my parents, Hans and José Heijnen

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ABSTRACT

Heijnen, Michel J.H. Ph.D., Purdue University, May 2016. Failures in Adaptive Locomotion in Heathy Young Adults. Major Professor: Shirley Rietdyk.

Young adults fall most frequently when walking, and trips account for 25% of these falls (Heijnen & Rietdyk, 2016). Common approaches to understanding tripping include the examination of behavior when a stationary obstacle is crossed successfully, or to deliberately trip the participant with a covert obstacle. However, these approaches do not establish the underlying cause of failure; examining inadvertent failures does, as this occurs most often in the field (Heijnen & Rietdyk, 2016). In order to identify the behavior that results in obstacle contact, this dissertation examined gait characteristics during inadvertent failures and manipulated the sensory information available to guide the limb trajectory. Manipulating the availability of sensory information is important to determine the information used to successfully guide the limbs, particularly the trail limb. Three experiments were conducted to systematically examine the role of visual and somatosensory information in young adults. I hypothesized that young adults would contact the obstacle due to incorrect foot placement when visual and somatosensory information were not manipulated. I hypothesized that healthy young adults would be able to use an obstacle memory to successfully cross the obstacle when both feedforward visual information and somatosensory information regarding obstacle contact were not available. Finally, I hypothesized that healthy young adults would progressively decrease foot clearance, resulting in values that would result in contact if the obstacle were still in place, when somatosensory information regarding obstacle contact was not available. My work has increased the understanding of several factors related to adaptive locomotion: failures, obstacle memory, and limb independence. First, obstacle contacts occurred most frequently with the trail limb and were mainly due to inadequate foot elevation. Obstacle contacts were caused by a progressive decrease in foot elevation with repeated trials in combination with high variability. Second, humans used an obstacle memory to guide the trail limb over the obstacle, and visual information gathered while walking up to the obstacle was important to establish this obstacle memory. Knowledge of results (i.e. failures) was used to update the obstacle memory. Finally, different behavior between the lead and the trail limb supported the argument that the limbs are controlled independently. Overall, a wide variety in behavior between participants was observed, highlighting the difficulties in developing a universal fall-prevention program. My work has expanded the understanding of adaptive locomotion by establishing the cause of inadvertent failures and the sensory information used to establish an obstacle memory in order to ensure safe travel through a cluttered environment.

CHAPTER 1. INTRODUCTION

1.1 Introduction

Falls are a major public health problem as they are common and lead to serious consequences (WHO). Most of the research on falls has focused on older adults, but it is important to note that in the US, falls are the leading cause of nonfatal injuries in adults aged 18-35 years, accounting for 15% of all injuries in this age group (CDC). It is important to understand the mechanisms that result in the failure to maintain balance, in order to develop effective interventions. Trips, defined as the swing limb contacting an obstacle in the environment, are a common occurrence in everyday life (Heijnen & Rietdyk, 2016). While not all trips result in a fall, trips are one of the main causes of falls in young adults (Heijnen & Rietdyk, 2016; Talbot, Musiol, Witham, & Metter, 2005). Therefore, it is important to identify the factors that are associated with a trip. Common approaches to understanding tripping include the examination of behavior when a stationary obstacle is crossed successfully, or to deliberately trip the participant with a covert obstacle. However, these approaches do not establish the underlying cause of failure; examining inadvertent failures does, as this occurs most often in the field (Heijnen & Rietdyk, 2016). My dissertation will not only examine kinematic gait characteristics during successful trials, but will also examine these characteristics during inadvertent failures in order to identify the behavior that results in obstacle contact

Examining failures provides vital information regarding the cause of the contact in animals (Setogawa, Yamaura, Arasaki, Endo, & Yanagihara, 2014) and humans (Chou & Draganich, 1998; Corporaal, Swinnen, Duysens, & Bruijn, 2016; Heijnen, Muir, & Rietdyk, 2012a; Heijnen, Romine, Stumpf, & Rietdyk, 2014; Patla & Greig, 2006). Obstacle contacts are either caused by incorrect foot placement (Chou & Draganich, 1998; Patla & Greig, 2006), or inadequate foot elevation (Heijnen et al., 2012a) (Figure 1). These failures often result from inadequate visual information regarding the obstacle (Mohagheghi, Moraes, & Patla, 2004; Patla & Greig, 2006; Rietdyk & Rhea, 2011).

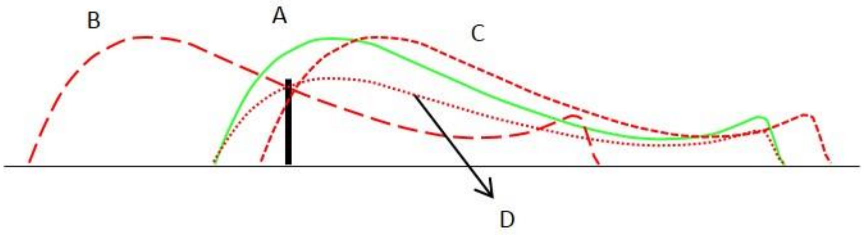

Figure 1 Successful trail limb trajectory (green) over an obstacle (A), and unsuccessful trail limb trajectories (red). Unsuccessful trajectories resulted in obstacle contact due to incorrect foot placement (B and C), or inadequate foot elevation (D).

When vision is available, it is the primary source of information used to detect obstacles (Patla, 1998; Pearson & Gramlich, 2010). Visual information regarding the obstacle is sampled in two ways, including feedforward (i.e. information sampled at a distance before obstacle crossing) and online (i.e. information sampled during the swing phase as the foot crosses the obstacle) (Table 1). Previous research has demonstrated that obstacle *height* information is adequately sampled in a feedforward manner during the approach phase (when the person is walking up to the obstacle) to provide appropriate foot elevation; however, obstacle *position* information must be sampled online to implement appropriate foot placement (Patla & Greig, 2006). The importance of visual information regarding the obstacle in order to successfully cross the obstacle is readily apparent by examining failures when vision has been manipulated. Failure rates increased when vision was completely removed, partially obstructed, or distorted (M. S. Alexander, Flodin, & Marigold, 2011; Johnson, Buckley, Scally, & Elliott, 2007; Menant, St George, Sandery, Fitzpatrick, & Lord, 2009; Mohagheghi et al., 2004; Patla & Greig, 2006; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006). Failure rates also increased when vision was not manipulated, but visible characteristics of the obstacle were reduced (Rietdyk & Rhea, 2011).

Table 1 A general overview of the sensory information available to the lead (first limb to cross the obstacle) and the trail limb (second limb to cross the obstacle).

	Lead Limb	Trail Limb
Vision		
• Feedforward o Obtained from previous trials	✓	✓
• Feedforward o Obtained from approach in current trial	✓	✓
• Online o Obtained during obstacle crossing in current trial	✓	✗
Somatosensory		
• Knowledge of Results (KR) o Obtained in current trial	✓	✓
• Proprioception o Obtained during obstacle crossing in current trial	✓	✓

Examination of the sensory information that is available to guide the limb trajectory is important to determine why people contact a stationary visible obstacle. Information available to guide the lead limb (first limb to cross the obstacle) includes feedforward visual information gathered during approach phase, online visual information, and somatosensory information (Table 1). Vision provides information about the obstacle characteristics, and the position of the person relative to the obstacle. Somatosensory provides information about the limb movement and position, including contact with the environment. Information available to guide the trail limb (second limb to cross the obstacle) is limited to feedforward visual information and somatosensory information (Table 1). To successfully cross the obstacle, knowledge of obstacle characteristics must be available for the trail limb since online vision is not available. This obstacle knowledge is created from information gathered during the approach and/or from previous interactions with the same or similar obstacles. The term “obstacle memory” will be used to refer to the knowledge of obstacle characteristics to be consistent with other researchers in this area (McVea & Pearson, 2006, 2007; Setogawa et al., 2014; Shinya, Popescu, Marchak, Maraj, & Pearson, 2012; Whishaw, Sacrey, & Gorny, 2009).

This dissertation will examine the contributions of visual and somatosensory information to the inadvertent trips that occur regularly for young healthy individuals (Heijnen & Rietdyk, 2016). These three studies extend the knowledge gained from an existing series of research articles that have manipulated various aspects of visual and somatosensory information. The current studies range from full availability of feedforward visual information and somatosensory information regarding contact (Study 1, Chapter 3), to obstacle crossing without the availability of either sensory source (Study 2, Chapter 5), and finally, the partial availability of sensory information (Study 3, Chapter 7).

First, in order to fully understand why failures occur, it is important to examine failures without any manipulations or constraints (i.e. inadvertent failures), as this is what typically occurs in the field. In the preceding research on failures, the obstacle contacts were induced with visual manipulations or foot placement constraints (Chou & Draganich, 1998; Patla & Greig, 2006). Using manipulations that induce failure is advantageous because the data collection can be minimized, as inadvertent failures are relatively rare. However, to examine just one or two inadvertent failures in each participant, the obstacle must be stepped over repeatedly (up to 300 times). In my first study, young adults will cross a stationary, visible obstacle without any manipulations to determine the frequency of inadvertent obstacle contacts in a laboratory setting and to quantify the gait characteristics that lead to inadvertent obstacle contact and also to determine the frequency of obstacle contacts (Chapter 3).

Second, the role of visual feedforward information and somatosensory information in the development of an obstacle memory will be assessed. The contribution of feedforward visual information to an obstacle memory is highlighted by several studies. Humans and animals are able to successfully cross an obstacle with the trail limb or hind limbs after straddling an obstacle for at least two minutes, indicating that the information gathered during approach and lead limb crossing is maintained and available to guide the trail or hind limbs (Lajoie, Bloomfield, Nelson, Suh, & Marigold, 2012; McVea & Pearson, 2006; Pearson & Gramlich, 2010; Whishaw et al., 2009). Furthermore, humans are able to successfully cross an obstacle when vision is removed three steps prior to crossing the obstacle (Mohagheghi et al., 2004), but failure rates increase when vision is removed during the final five steps of the approach (Patla & Greig, 2006). Thus, when vision was unavailable for a longer duration, participants were unable to update the feedforward information. More specifically, participants elevated the limbs adequately but foot placement was incorrect, indicating that feedforward obstacle *height* information was sampled adequately during the approach but obstacle *position* information needs to be sampled online. The contribution of somatosensory information regarding obstacle contact is highlighted by Rhea and Rietdyk (2011), who observed an increase in foot elevation following obstacle contact. The somatosensory information from the obstacle contact provides knowledge of results, which can be used to update the obstacle memory. The preceding research is extended in the experiment in Study 2 (Chapter 5). Online obstacle position information was provided, but feedforward obstacle height information during the approach phase and somatosensory information regarding obstacle contact were removed completely. Participants needed to use an obstacle height memory, provided by interaction with the obstacle in preceding trials. The purpose of Study 2 is to determine whether an obstacle height memory can accurately guide the feet over an obstacle when online position information is always available.

Finally, the role of somatosensory information regarding obstacle contact is examined. As stated above, the information available to guide the trail limb is limited to feedforward visual information and somatosensory information. In Study 1, there was a drift in the foot clearance measure with repeated trials, in which the clearance progressively decreased by about 1 mm per trial, which continued until the trail foot contacted the obstacle. A similar drift has also been observed in upper limb tasks (Ambike, Zatsiorsky, & Latash, 2015; Vaillancourt & Russell, 2002), and it is argued by one group that the drift reflects a drift in memory (Vaillancourt & Russell, 2002) or a drift in the referent coordinates (Ambike et al., 2015). In the locomotor task, the drift results in the foot clearance reaching zero and thus obstacle contact occurs. The somatosensory information from the obstacle contact provides knowledge of results, which can be used to update the feedforward information. The large increase in toe clearance after contact (Rhea & Rietdyk, 2011) is consistent with an updating of the memory following knowledge of results. In Study 3, this knowledge of results was removed (Chapter 5). Participants crossed an obstacle with the lead limb, but directly following lead limb crossing, the obstacle dropped down. Unlike previous studies (Lajoie et al., 2012; McVea & Pearson, 2006; Whishaw et al., 2009), the participants did not pause while straddling the obstacle. They walked smoothly and continuously, and they were not aware that the obstacle had been lowered for the trail limb crossing. Two different types of behavior were possible: 1) a linear decrease in trail foot clearance, resulting in values that would result in contact if the obstacle was still in place, or 2) an exponential decrease, with the flat region value similar to the height of the obstacle. A linear decrease would indicate that the obstacle height memory drifts over time, and somatosensory information following obstacle contact is used to update the obstacle memory. An exponential decrease with the flat region at or above the obstacle height would indicate that feedforward visual information is accurately guiding the trail limb and the obstacle memory is apparently becoming more accurate with each successive trial. The purpose of this study is to determine if physical contact is necessary to update the feedforward visual information regarding the obstacle height (Chapter 7).

The overall goal of the dissertation is to examine inadvertent failures in order to identify the behavior that results in obstacle contact and to determine what sources of sensory information are necessary to guide the behavior such that obstacle contacts are minimized. The following specific aims will be addressed in this dissertation.

1.2 Specific Aim 1

To identify the gait characteristics that lead to inadvertent obstacle contact in healthy young adults; in particular, do inadvertent failures result from inappropriate foot placement or inappropriate foot elevation?

1.2.1 Hypothesis

It was hypothesized that young adults would contact the obstacle due to incorrect foot placement (placing the foot too close to the obstacle).

1.3 Specific Aim 2

To determine the contribution of visual and somatosensory information to accurately guide the lower limb trajectory over an obstacle in healthy young adults; in particular, whether an obstacle memory can accurately guide the foot over an obstacle when online position information is always available.

1.3.1 Hypothesis

It was hypothesized that healthy young adults would be able to use obstacle height information, obtained in a feedforward manner from visual information, to successfully clear an obstacle at least 95% of the time.

1.4 Specific Aim 3

To determine the contribution of somatosensory information to accurately guide the lower limb trajectory over an obstacle in healthy young adults; in particular, to determine if physical contact is necessary to update the obstacle height memory.

1.4.1 Hypothesis

It was hypothesized that healthy young adults will continue to progressively decrease foot clearance, resulting in values that would result in contact if the obstacle was still in place, indicating that physical contact is necessary to update the memory regarding the obstacle height.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This section reviews research that examines failures of adaptive locomotor behavior during daily activities. I will first highlight the problem by discussing the frequency of failures in field. Second, I will discuss the importance of adaptive locomotion in examining failures. Finally, I will discuss inadvertent failures in a laboratory setting, including the role of visual information to guide the lead (first limb to cross the obstacle) and trail limbs (second limb to cross the obstacle) during adaptive locomotion.

2.2 Epidemiology of Falls

In the US, falls are the third leading cause of unintentional injury deaths in adults across all ages, accounting for 23% of these deaths (CDC). Falls are the leading cause of nonfatal injuries in adults across all ages, accounting for 28% of all injuries (Figure 2) (CDC). The percentage of unintentional injuries due to a fall decreases from approximately 40% during the first few years of life to about 15% during adolescence, followed by a gradual increase to over 70% in older adults (Figure 2). Furthermore, the total number of incidences per 1000 people follows a similar trend (Figure 2). As the injury data indicates, this group of healthy individuals experiences the least fall-related injuries per 1000 people, which suggests that their ability to maintain upright posture is optimal. Note, however, that they still experience a substantial number of injuries (Figure 2).

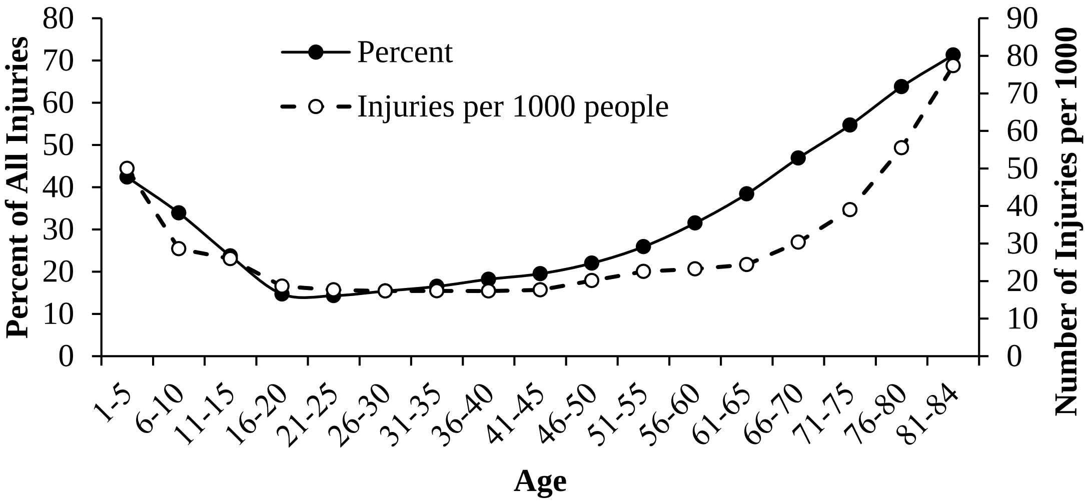

Figure 2 Percent and total number of nonfatal injuries treated in a hospital emergency department due to an unintentional fall per age group. Values obtained from 17 Tables for the year 2013 (CDC).

Older adults fall more often, and have more fall-related injuries than younger adults, therefore frequency and circumstances of falls are largely examined in older adults. As reviewed by Rubenstein and Josephson (2002), 30 to 60% of adults 60 years and older reported falling at least once in the past year. One to 11% of these falls resulted in fractures or other serious injuries. Falls in older adults occur most frequently during walking (Berg, Alessio, Mills, & Tong, 1997; Talbot et al., 2005); trips (34%) and slips (25%) are the main perceived causes of falls in older adults (Berg et al., 1997).

Falls are prevalent in younger age groups as well, as indicated by the high percentage of incidences reported by the Centers for Disease Control and Prevention (CDC) (Figure 2) but these young age groups are understudied for fall frequency and circumstances. Only two publications have examined frequency and circumstances in young adults (Heijnen & Rietdyk, 2016; Talbot et al., 2005). The former authors reported that 52% of the young adults fell at least once in the past 16 weeks; 16% of these falls resulted in injury. Falls occurred most frequently during walking (58%), and a slip (48%) or trip (25%) was the most common perceived cause. The frequency and circumstances of falls in young adults are similar to older adults, making this population ideal to establish a baseline to which balance-compromised groups can be compared in the future.

2.3 Adaptive Locomotion

Adaptive locomotion is more demanding than unobstructed locomotion, and tasks that are more challenging are better able to distinguish people with compromised ability (N. B. Alexander et al., 1995; Cantin et al., 2007; Vallée et al., 2006). Furthermore, trips are one of the main causes of a fall in young adults (Heijnen & Rietdyk, 2016; Talbot et al., 2005). Examining factors that lead to obstacle contact, including the role of sensory information during adaptive locomotion, will increase our understanding of failures.

Vision plays a crucial role in providing information during adaptive locomotion as it allows animals to sample information about the environment from a distance. Visual information can be modified by 1) complete removal of vision during the approach phase with the use of liquid crystal goggles (Mohagheghi et al., 2004; Patla & Greig, 2006), 2) partial removal of vision by obstructing the lower visual field using basketball goggles (Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), 3) distorting vision by using prism glasses or multifocal glasses (M. S. Alexander et al., 2011; Johnson et al., 2007; Menant et al., 2009), or 4) modifying characteristics of the obstacle so they are not visible (Rietdyk & Rhea, 2011). All of these visual manipulations increase the failure rate, especially in the lead limb, indicating that young adults rely on visual information to ensure successful clearance over an obstacle.

Young adults contact the obstacle most frequently with the trail limb, as trail limb contacts ranged from 67 to 100% (Berard & Vallis, 2006; Heijnen et al., 2012a; Heijnen et al., 2014; Mohagheghi et al., 2004; Muir, Haddad, Heijnen, & Rietdyk, 2015; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). It is argued that trail limb contacts are more common due to the fact that the lead limb is visible in the lower visual field when crossing the obstacle and the trail limb is not (Patla, Rietdyk, Martin, & Prentice, 1996; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). Therefore, the lead limb relies on online visual feedback from the lower visual field to fine-tune the trajectory while crossing the obstacle. This interpretation is supported by the increase in foot clearance variability when the lower visual field is obstructed (Patla, 1998; Rhea & Rietdyk, 2007). Because the lead limb is visible during obstacle crossing and the trail limb is not, it is reasonable to predict that the behavior and/or feedback from the lead limb is used to control the trail limb. However, research has shown that there is only a weak correlation between foot clearances of the lead and trail limbs, which does not support this contention (Mohagheghi et al., 2004; Rietdyk & Rhea, 2006). Further, independent control of the limbs has been shown in a variety of locomotor tasks such as steady state gait (Yang et al., 2004), adaptive locomotion (Heijnen et al., 2012a; Heijnen et al., 2014; Niang & McFadyen, 2004; Patla et al., 1996), adaptive locomotion with lower visual field obstruction (Rhea & Rietdyk, 2011; Rietdyk & Rhea, 2006), and even hopping (Anstis, 1995). This independent control increases the adaptability of human locomotion in order to navigate safely through a cluttered environment (Patla, 1991). Failure to independently control the limbs during an obstacle crossing task may increase fall-risk.

In summary, the examination of obstacle crossing is a challenging locomotor task. Due to the important role that vision plays, this dissertation will focus on visual feedback. The effect of vision will be considered for the control of the lead and trail limbs separately, as the majority of the research indicates that they are controlled independently.

2.4 Failures in the Laboratory

The likelihood that an individual will experience a fall is termed fall-risk. Fall-risk in older adults can be determined by a variety of risk factors such as muscle weakness, vitamin D deficiency, gait and balance problems, number of medicines, vision problems, foot pain or poor footwear, and environmental hazards (CDC, 2015). My dissertation will focus on gait characteristics, more specifically, the ability to cross an obstacle. Previous research that determined fall-risk from gait characteristics during obstacle crossing has mainly focused on successful obstacle crossing trials. However, examining successful trials to determine fall-risk is inadequate because these trials do not establish the underlying cause of contact. Examining failures has provided critical information regarding the cause of the contact in both animals (Setogawa et al., 2014) and humans (Chou & Draganich, 1998; Corporaal et al., 2016; Heijnen et al., 2012a; Heijnen et al., 2014; Patla & Greig, 2006).

In a laboratory setting, failure rates with a stationary, visible obstacle are 1-2% (Berard & Vallis, 2006; Heijnen et al., 2012a; Heijnen et al., 2014; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), and as noted above, young adults contact the obstacle most frequently with the trail limb (Berard & Vallis, 2006; Heijnen et al., 2012a; Heijnen et al., 2014; Mohagheghi et al., 2004; Muir et al., 2015; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). As mentioned previously, failures with the trail limb are more common than lead limb failure due to the fact that the lead limb is visible when crossing the obstacle, and the trail limb is not (Patla et al., 1996; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011).

Failures can be induced in the laboratory to examine if people can recover from a perturbation or to examine why people contact an obstacle. One induced failure approach uses a concealed and/or suddenly appearing obstacle that perturbs the participant, who then has to react to the sudden perturbation to avoid falling (Brown, Doan, McKenzie, & Cooper, 2006; Eng, Winter, & Patla, 1994; Pijnappels, Bobbert, & van Dieėn, 2001; Weerdesteyn, Nienhuis, Hampsink, & Duysens, 2004). These induced failures provide information regarding strategies for recovery (Eng et al., 1994). Although this reactive paradigm provides important information, it does not increase the understanding of why a person contacts a visible, stationary obstacle, which is a frequent cause of falls in young adults (Heijnen & Rietdyk, 2016; Talbot et al., 2005).

Another category of induced failures in the laboratory uses a stationary object, but other factors are manipulated to examine the cause of contact. These factors are manipulated directly (e.g. by constraining foot placement) or indirectly (e.g. by removing vision) to determine the cause of failures. Obstacle contacts are caused by incorrect foot placement (Chou & Draganich, 1998; Patla & Greig, 2006) or inadequate foot elevation (Heijnen et al., 2012a) (Figure 1). Figure 1 shows successful (green) and unsuccessful (red) trail limb trajectories. Failures result from incorrect foot placement too far from the obstacle (trajectory B), incorrect foot placement too close to the obstacle (trajectory C), or inadequate foot elevation (trajectory D). Incorrect foot placement was found to be the main cause of contact when foot placement was constrained with instruction (Chou & Draganich, 1998), or when vision was removed with the use of liquid crystal goggles (Patla & Greig, 2006). A decrease in distance between the toe and obstacle (i.e. a closer foot placement to the obstacle) increased the number of failures (Chou & Draganich, 1998). As the foot is placed closer to the obstacle, the time available to flex the knee before obstacle crossing reduces. This leads to a lower foot clearance and is expected to result in more failures. An increase in angular knee velocity would prevent obstacle contact and is suggested to be of primary importance in obstacle avoidance (Chou & Draganich, 1998). Similarly, incorrect foot placement resulted in obstacle contacts when vision was removed five steps prior to crossing the obstacle (Patla & Greig, 2006). Foot elevation remained adequate in this experiment, leaving the authors to conclude that height information was sampled in a feedforward manner, while online visual information was needed for correct foot placement.

In all of the preceding research on failures, failures were induced with visual manipulations or foot placement constraints. Using manipulations that induce failure is advantageous because the data collection can be minimized, as inadvertent failures are relatively rare. However, in order to fully understand why failures occur, it is important to also examine failures without any manipulations or constraints, as this is what typically occurs in the field. When inadvertent failures were examined with self-selected foot placement and full vision (i.e. no manipulation of foot placement or vision), the majority of failures (90%) were due to inadequate foot elevation (Heijnen et al., 2012a).

Previous studies have often examined adaptive locomotion with full vision. The role of vision during adaptive locomotion can be examined by systematically manipulating visual information about the environment during different phases of the locomotor task (Mohagheghi et al., 2004; Patla, 1998; Patla & Greig, 2006), by reducing visible characteristics of the obstacle (Rietdyk & Rhea, 2011), or by inducing visual illusions about the obstacle height (D. B. Elliott, Vale, Whitaker, & Buckley, 2009; Foster, Hotchkiss, Buckley, & Elliott, 2014; Foster, Whitaker, Scally, Buckley, & Elliott, 2015; Rhea, Rietdyk, & Haddad, 2010). Obstacle height and position are sampled in a feedforward manner and knowledge of the obstacle characteristics is important to successfully cross an obstacle (Mohagheghi et al., 2004; Patla, 1998; Patla & Greig, 2006). The terminology of this knowledge is controversial, and has been termed a “stored obstacle representation” (Lajoie et al., 2012) or an “obstacle memory” (McVea & Pearson, 2006, 2007; Setogawa et al., 2014; Shinya et al., 2012; Whishaw et al., 2009). The term “obstacle memory” will be used in my dissertation when referring to the feedforward information of obstacle characteristics. Cats (McVea & Pearson, 2006), horses (Whishaw et al., 2009), and humans (Lajoie et al., 2012) can accurately scale trail limb trajectories when straddling an obstacle for extended periods of time. In these studies, the obstacle was lowered while straddling an obstacle in order to examine if an obstacle memory can accurately guide trail limb trajectories. The animals were able to update the obstacle memory during the approach phase (as they walked toward the obstacle). Recall the experiment when the obstacle was visible during the initial part of the approach phase, but then vision was removed so that they were unable to update feedforward information during the final five steps of the approach (Patla & Greig, 2006). The obstacle contacts in that experiment were due to incorrect foot placement, not inadequate foot elevation. These findings indicate that, although participants were able to rely on obstacle height information sampled in a feedforward manner during the initial part of the approach phase, obstacle position information needs to be sampled online for successful obstacle negotiation (Patla & Greig, 2006). This research is extended in the experiment in Chapter 5. Online obstacle position information was provided, but feedforward obstacle height information was removed completely during the approach phase. Participants needed to rely on feedforward height information, provided by interaction with the obstacle in preceding trials, to determine if feedforward height information could accurately guide the lower limb trajectory over an obstacle.

As mentioned previously, the lead limb is visible in the lower visual field and can rely on online visual information to fine-tune the limb trajectory while the trail limb cannot. The importance of online visual information is highlighted by Rhea et al. (2010). When a height illusion made one obstacle appear higher than another, participants initially increased lead limb elevation when stepping over the larger looking obstacle. However, after receiving online visual information of the limb position relative to the obstacle from crossing the obstacle, limb elevation decreased to values similar to the obstacle that appeared smaller. Thus, although feedforward information indicated that the obstacle was higher than it was, online visual information from crossing the obstacle appeared to update the memory, and the illusion no longer affected the crossing behavior. The trail limb does not receive online visual information of the limb position relative to the obstacle; the information available to guide the trail limb includes feedforward visual information and somatosensory information. Vision provides information about the obstacle characteristics, and the position of the person relative to the obstacle. Somatosensory provides information about the limb movement and position, including contact with the environment. With each trial of stepping over the obstacle, the trail limb clearance progressively decreased, and the decrease appeared unintentional as it progressively continued until the foot contacted the obstacle (Heijnen et al., 2012a). The decrease in foot clearance can be described as ‘drift’, this drift has also been observed in upper limb tasks (Ambike et al., 2015; Vaillancourt & Russell, 2002). In the locomotor task, the drift results in the foot clearance reaching zero, and somatosensory information from the obstacle contact provides knowledge of results regarding the limb being too low, which can be used to update the obstacle memory.

The large increase in trail foot clearance after contact is consistent with an updating of the obstacle memory following knowledge of results. Following trail limb obstacle contact, trail foot elevation increased 75% (Heijnen et al., 2012a; Rhea & Rietdyk, 2011). Thus, it appears that knowledge of results (failure or success in crossing obstacle) from somatosensory information was used to guide the trail limb trajectory in the following trials, or to update the obstacle memory used to control the trail limb. Although this knowledge of results appears to be adequate in controlling the trail limb, the 75% increase in foot elevation suggests that, unlike visual information, somatosensory information is unable to precisely control movement of the lower limb trajectory. In Study 3, knowledge of results will be removed to examine the role of somatosensory information regarding obstacle contact. The obstacle will drop down after the lead limb crosses, so that if the trail foot clearance is too low, there won't be somatosensory information resulting from the physical contact providing knowledge of results. This manipulation will increase the understanding of the role of somatosensory information to accurately guide the lower limb trajectory over an obstacle.

In summary, examining failures provides critical information regarding the cause of contact. Contacts are either due to incorrect foot placement, or inadequate foot elevation. Obstacle height (sampled in a feedforward manner during the approach) and position (sampled online) are critical pieces of information to successfully cross an obstacle. Providing online obstacle position information, but removing obstacle height information during the approach, will allow for the examination of an obstacle height memory to accurately guide the lead and trail limb over an obstacle. Providing obstacle height and position information, but removing obstacle contact information during the swing phase of the trail limb, will allow for the examination of somatosensory information to guide the trail limb over an obstacle.

CHAPTER 3. FACTORS LEADING TO OBSTACLE CONTACT DURING ADAPTIVE LOCOMOTION

This study has already been completed and published in Experimental Brain Research (Heijnen et al., 2012a). The full text is reprinted below with permission from Springer, provided by the Copyright Clearance Center.

3.1 Specific Aim

To identify the gait characteristics that lead to inadvertent obstacle contact in healthy young adults; in particular, do inadvertent failures result from inappropriate foot placement or inappropriate foot elevation?

3.2 Abstract

During everyday life, healthy adults occasionally trip over an obstacle that they knew was there. These ‘spontaneous’ trips can provide insight into the circumstances leading to trips and falls. The goal of this study was to describe the errors in foot placement and/or foot elevation that resulted in a spontaneous contact with a fixed, visible obstacle in young, healthy adults. Fifteen subjects stepped over an obstacle (height set to 25% leg length) placed in the middle of an 8 m walkway, up to 300 times. Three subjects never contacted the obstacle and 12 subjects contacted the obstacle 1–4 times, totaling 24 contacts in 3,843 trials (0.6%). Most of the contacts (92%) were with the trail limb.

Minimum foot clearance of the trail limb (trail MFC) decreased linearly (average slope of −1 mm/trial) with repeated trials. The majority of subjects (70%) continued the linear decrease of trail MFC until they contacted the obstacle. The remaining contacts resulted from an apparent misjudgment of foot placement and/or foot elevation. Following contact, trail MFC increased 75% in the subsequent trials and remained elevated at least up to 30 trials post-contact, but the trajectory of the unperturbed lead limb did not change, further supporting the idea of independent control for the lead and trail limbs during obstacle crossing. Possible causes of the progressive decrease in trail MFC until obstacle contact are considered.

3.3 Introduction

Falls have a detrimental impact on health, independence, and quality of life across all ages (Kannus, Sievänen, Palvanen, Järvinen, & Parkkari, 2005; Leamon & Patrice, 1995; Lipscomb, Glazner, Bondy, Guarini, & Lezotte, 2006; Verghese et al., 2006). In order to mitigate falls, it is important to understand the factors that lead to a fall. Thirty-four to fifty-three percent of falls result from a trip (Berg et al., 1997; Blake et al., 1988); thus, examination of tripping behavior is a logical starting point. Fall risk from tripping can be assessed by unexpectedly tripping the participant (e.g., Eng et al., 1994; Pijnappels et al., 2001) or determining the ability to avoid a suddenly appearing obstacle (e.g., Brown et al., 2006; Weerdesteyn et al., 2004). However, while crossing the street with full vision, healthy adults occasionally trip over the curb that they knew was there. Although these ‘spontaneous’ trips are rare, their examination will provide further insight into the circumstances that result in a trip and possible fall.

A few studies have quantified obstacle contact during overground locomotion with a stationary obstacle. Higher numbers of obstacle contacts in a laboratory setting were observed in people with Alzheimer’s disease (N. B. Alexander et al., 1995) and in older adults with fall risk classification (Di Fabio, Kurszewski, Jorgenson, & Kunz, 2004). In young, healthy adults, contacts were associated with placement of the trail foot (second foot to cross the obstacle); as the distance between the trail foot placement and the obstacle decreased, the number of trail foot contacts increased (Chou & Draganich, 1998). This relationship was determined by constraining foot placement with instructions. Obstacle contact has also been associated with visual manipulations that interfere with the perception of obstacle characteristics. These manipulations include no vision during approach (Patla, 1998; Patla & Greig, 2006), multifocal glasses (Johnson et al., 2007), dual task combined with multifocal glasses (Menant et al., 2009), visibility of obstacle characteristics (Rietdyk & Rhea, 2011), and wearing prisms (M. S. Alexander et al., 2011). Patla and Greig (2006) examined the foot trajectories to determine the cause of failures when vision was not available during approach and found that incorrect foot placement before the obstacle resulted in obstacle contact, not inappropriate limb elevation. In summary, two studies have examined the cause of obstacle contact with a known and fixed obstacle in young, healthy adults, and both studies found that incorrect foot placement resulted in failures (Chou & Draganich, 1998; Patla & Greig, 2006). In the two studies, contact likelihood was increased by constraining foot placement or removing vision. To fully understand the behavior leading to spontaneous contacts, it is important to also examine self-selected foot placement under normal visual conditions.

Our first objective was to describe the behavior that resulted in spontaneous obstacle contacts with normal lighting, full vision, and high contrast obstacles for young, healthy subjects. This behavior includes the foot placement and clearance of the spontaneous contact trial in comparison with the successful trials preceding the contact (pre-contact epoch). We hypothesized that obstacle contacts will result from an anomalous trail foot placement (too close to the obstacle). Our second objective was to quantify the obstacle crossing behavior in the trials following an obstacle contact (post-contact epoch). Research on a limited number of observations found that a single spontaneous obstacle contact had a lasting impact on subsequent obstacle crossing behavior, but only for the limb that contacted the obstacle (i.e., trail limb) (Rhea & Rietdyk, 2011). Following an obstacle contact, we hypothesized that the foot clearance of the ipsilateral limb will be higher in the first trial after the contact and will decrease gradually with repeated obstacle crossings.

3.4 Methods

Fifteen young, healthy subjects participated (22.2 ± 1.9 years, 8 males). Subjects were free from any impediments to normal locomotion and had normal or corrected-to-normal vision, as verified by self-report. All subjects signed a consent form approved by the local Institutional Review Board.

Subjects walked at a self-selected pace on an 8-m walkway and stepped over an obstacle in the middle of the walkway. The obstacle height was 25% of the subject’s leg length (obstacle height ranged from 19.5 to 26.0 cm, in 0.5-cm increments; 100-cm wide, 0.3-

cm deep). The obstacle was composed of Masonite board, painted flat black and designed to tip if contacted (similar to a hurdle).

Subjects were not told that obstacle contacts were of interest. Subjects self-selected which foot would cross the obstacle first (lead foot). At least 250 trials were collected. If obstacle contact occurred during the last 50 trials, 50 more trials were collected after the contact, up to a maximum of 300 trials. No practice trials were given. Subjects received a short break every 50 trials. Obstacle contacts were noted during data collection. If a contact occurred, at least 50 trials after the contact were collected before the next break was provided. Data collection took up to 100 min, and the total distance covered was 4 km (250 trials) to 4.8 km (300 trials).

Infrared emitting diodes (IREDs) were placed on the lateral aspect of the left foot at the distal phalanx of the third toe, calcaneus, and malleolus and on the medial aspect of the right foot at the distal phalanx of the first toe, calcaneus, and malleolus. Two IREDs were placed on the left temporal region of the head, and one IRED was placed on the top of the obstacle. Two Optotrak 3020 sensors (NDI, Waterloo, Canada) recorded the IRED positions at 60 Hz.

Data were analyzed with MATLAB 2010a software (MathWorks Inc., MA, USA) and filtered offline at 8 Hz with a fourth-order zero-phase-shift low-pass Butterworth digital filter (Winter, 2009). The instant when the foot is directly over the obstacle is not typically captured due to high foot velocities, resulting in clearance errors. Heijnen et al.

(2012b) validated the use of a cubic interpolation to upsample toe trajectories to 600 Hz, reducing maximum trail toe clearance errors of 17% to 4%. The same cubic interpolation was used here before clearances were calculated. Toe clearance was calculated as the vertical distance between the toe and obstacle IREDs, at the frame when the toe IRED crossed the obstacle. Heel clearance was calculated as the vertical distance between the heel and obstacle IREDs, at the frame when the heel IRED crossed the obstacle. The minimum foot clearance (MFC) was the lowest value of toe or heel clearance, as the toe clearance measure can overestimate the foot clearance (Loverro, Mueske, & Hamel, 2013; Thies, Jones, Kenney, Howard, & Baker, 2011). Horizontal distance (HD) was calculated as the anterior-posterior (AP) distance between the toe and obstacle IREDs at toe-off. Stride length (SL) was calculated as the AP distance between the toe IRED during the stance phases before and after crossing the obstacle. Gait speed was calculated as average head AP velocity during obstacle crossing. Head AP displacement was differentiated with the central difference method to determine AP velocity, and the average was calculated from lead toe-off before the obstacle until trail toe-off after the obstacle, which includes both lead and trail foot crossing the obstacle. MFC, HD, and SL were calculated for both the lead and trail limb.

If an obstacle was contacted, that trial number was set as ‘0’, and trials were windowed to include 50 trials before contact (pre-contact epoch) and 50 trials after contact (post-contact epoch). A 50-trial epoch captures changes in behavior over a longer time scale, approximately 15 min. Due to the spontaneous nature of the contacts, one subject did not have 50 pre-contact trials because the contact occurred at trial 31; the pre-contact epoch was shortened to 30 trials for that subject (10 min). We chose to keep the remaining 9 subjects at 50 trials to capture changes over 15 min for most subjects. Similarly, a second contact occurred within the following 50 trials for most subjects, so the post-contact epoch was shortened to 30 trials, with three subjects having post-contact epochs shorter than 30 trials (17, 27, and 29 trials long). Second, third, and fourth contacts were examined in the same manner.

The foot trajectories of the contact trial and the preceding 10 successful trials were examined to classify cause of contact. Contacts were classified as inappropriate foot placement (trajectories B & C top panel, Figure 3) or inadequate elevation (trajectory D, top panel Figure 3) (Patla & Greig, 2006). Regressions were used to quantify the progressive decrease in MFC that was evident when examined as a function of trial number (Figure 4). First, both linear and quadratic regressions were calculated for each subject during the pre-contact epoch of the first contact to determine the nature of the decrease. The average R^2 values for all linear and quadratic regressions (significant and non-significant combined) were 0.13 and 0.17 for the lead MFC, respectively, and 0.25 and 0.28 for the trail MFC. When only significant regressions were included, the average R^2 for linear and quadratic regressions were 0.23 and 0.27, respectively, for the lead MFC (five regressions included) and 0.34 and 0.36 for the trail MFC (seven regressions) (Table 2). A marginal increase was observed with the quadratic regression, which is always expected with a higher-order regression. Therefore, linear regressions were used to quantify the changes over trials.

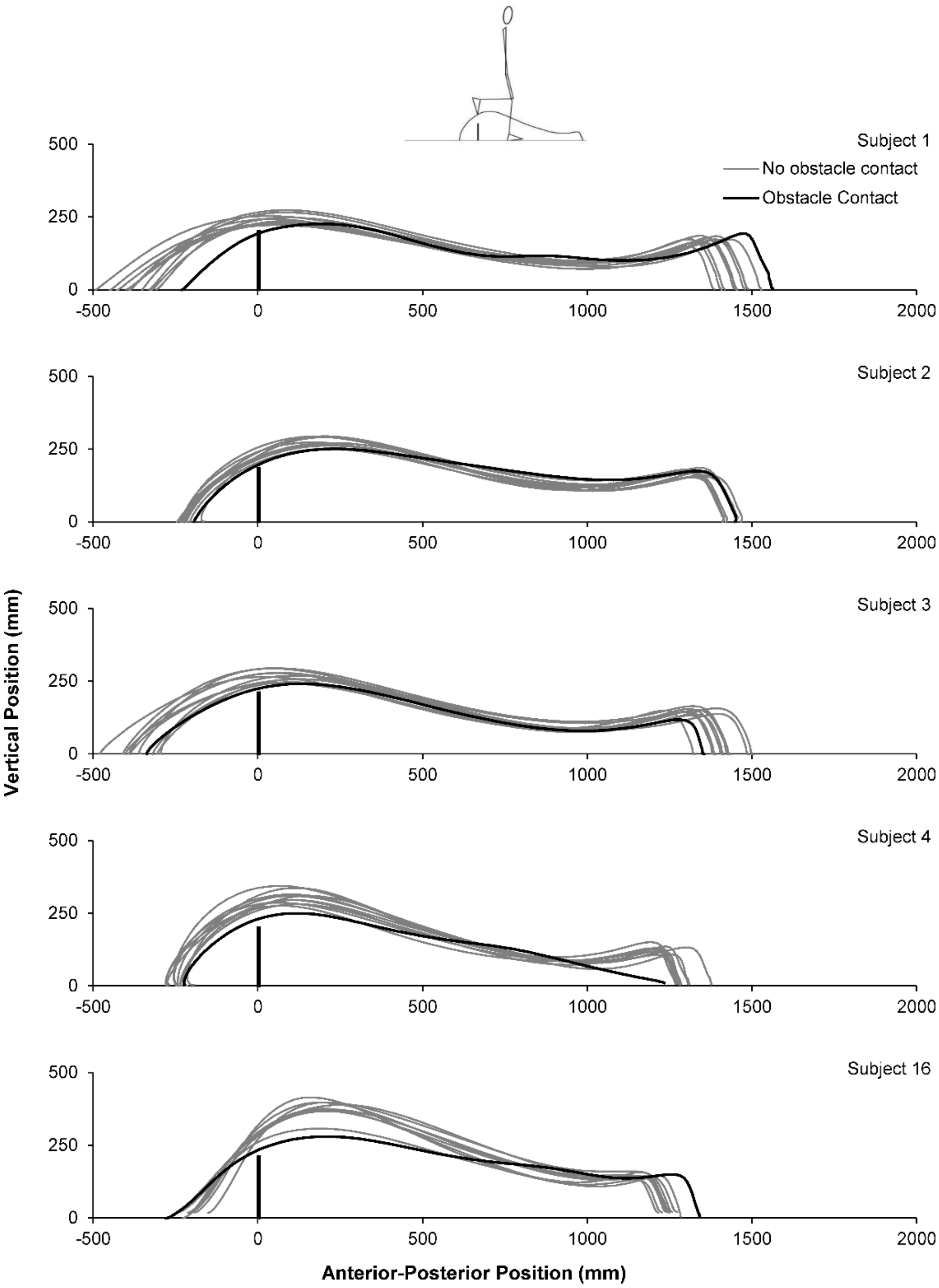

Figure 3 Toe trajectories of the trail limb for five subjects during the first obstacle contact trial (black line) and the preceding 10 successful trials (gray lines). The toe trajectory for the contact trial does not always go through the obstacle due to the location of the toe IRED, which was a small distance from the tip of the shoe. In the top of the figure, the four possible trail limb trajectories used to classify cause of failure are illustrated.

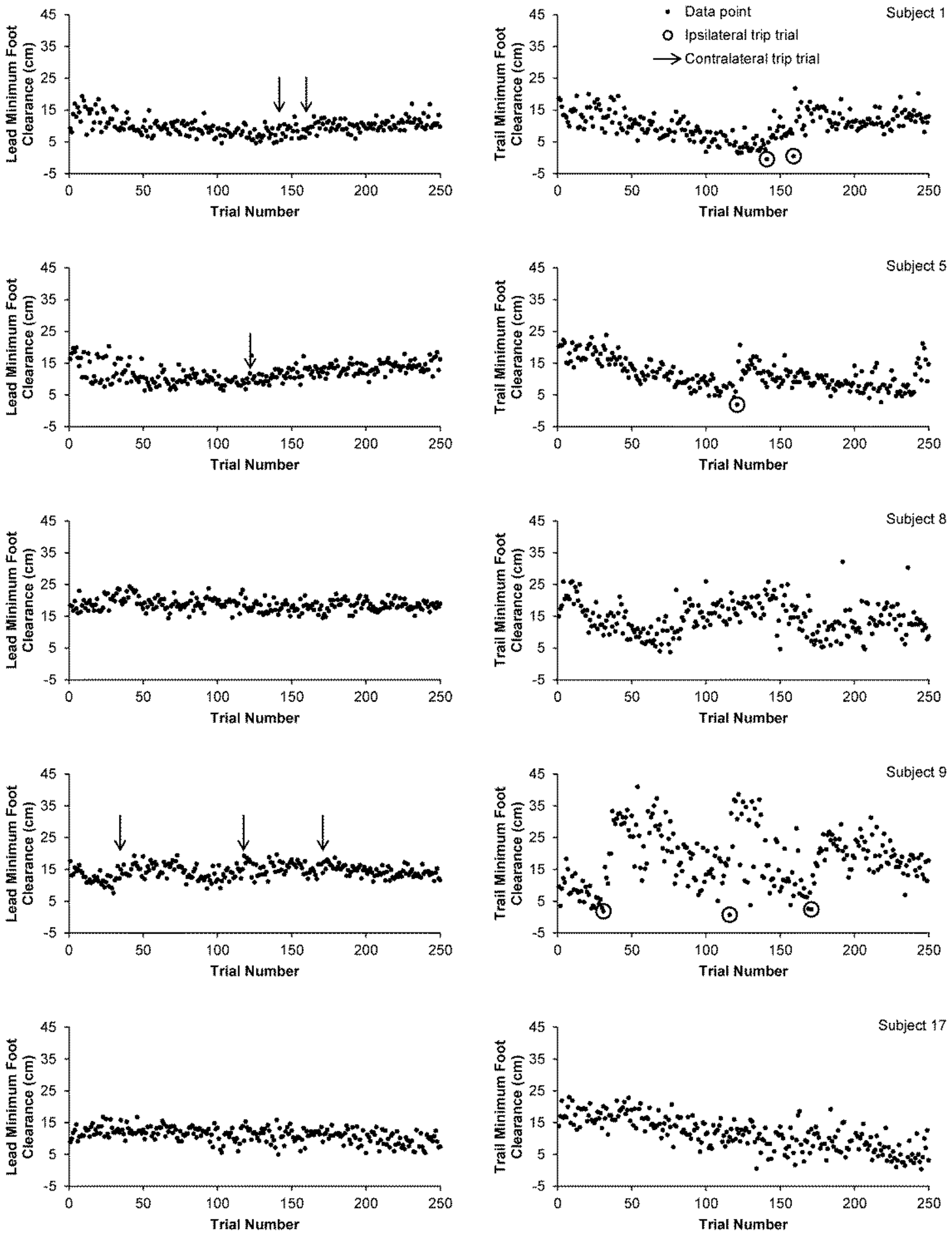

Figure 4 Minimum foot clearance (MFC) for the lead (left column) and trail (right column) limbs as a function of trial number for five subjects. The circled trials indicate that a contact occurred with the trail limb. The arrows indicate the corresponding MFC for the lead limb. Subjects 8 and 17 did not trip.

Table 2 Contact trial number and results of the individual regressions for the pre-contact epoch of the trail and lead minimum foot clearance (MFC) for the trail obstacle contacts. Results are grouped as a function of contact number. P values at $p \leq 0.01$ are bolded.

Subject	Contact trial number	Number of trials included	Trail MFC slope	p-value	Lead MFC slope	p-value
First Contact						
1	141	50	-0.8	**<0.001**	-0.5	**0.010**
2	102	50	-0.7	0.058	0.4	**<0.001**
3	69	50	-1.0	**<0.001**	-0.6	**0.008**
4	65	50	-1.2	**<0.001**	-1.2	0.183
5	121	50	-1.0	**<0.001**	-0.4	0.029
7	65	50	-2.6	**<0.001**	-0.4	**0.012**
9	31	30	-2.5	**<0.001**	-1.9	**<0.001**
14	155	50	-0.2	0.552	0.1	0.757
15	140	50	-0.8	**0.005**	-0.1	0.807
16	142	50	0.4	0.182	0.2	0.361
Summary of first trail contact						
Mean	103	Mean	-1.0		-0.4	
Median	112	SD	0.9		0.7	
Second Contact						
1	159	17	0.1	0.937	-0.4	0.725
2	152	49	-0.4	0.130	-0.4	**0.014**
3	239	50	-2.0	0.004	0.4	**0.020**
6	88	35	-1.6	**<0.001**	-0.1	0.804
7	95	29	0.2	0.748	-0.5	0.163
9	116	50	-2.8	**<0.001**	-0.5	**0.020**
12	89	2	-	-	-	-
15	168	27	0.5	0.264	0.4	0.534
16	206	50	-0.4	0.118	-0.3	0.309
Third Contact						
2	250	50	-0.6	**<0.001**	-0.3	**0.002**
9	171	50	-4.6	**<0.001**	0.0	0.903
Fourth Contact						
2	282	31	-1.2	**<0.001**	-0.3	0.147
Summary of trail contacts 2-4						
Mean	158	Mean	-1.1		-0.2	
Median	164	SD	1.5		0.3	

Linear regressions were conducted for each subject individually during the pre- and post-contact epochs, for each dependent variable (HD, MFC, SL, gait speed); these are called ‘individual regressions’. Due to the large number of regressions, the p value was set to $p \leq 0.01$ to reduce the likelihood of a false positive. To demonstrate the general change in behavior, each measure was also averaged across subjects for each trial in the pre- and post-contact epochs, and the linear regression was repeated on the average data; these are called ‘group regressions’.

Qualitative observations indicated that the progressive decrease in trail MFC appeared to continue until contact occurred (e.g., subject 5, Figure 3). To examine this quantitatively, for each subject a MFC region was defined as the mean minus two standard deviations of the pre-contact epoch. If the contact MFC was within the region, the subject was coded as ‘contact due to decreasing MFC’.

However, the decreasing trend across trials resulted in a higher standard deviation, increasing the likelihood that the contact MFC fell within the prescribed region. Therefore, for each subject, the linear decrease was removed from the pre-contact epoch with the detrend function in MATLAB (best straight-line fit was removed), and then the mean and standard deviation were calculated. Note that a standard ANOVA or t test could not be conducted to see if the contact trial was significantly different from the preceding trials, as the contact trial would, by definition, be lower than the non-contact trials.

To establish if MFC increased in the post-contact epoch relative to the pre-contact epoch, trials were divided into eight groups of ten trials each: A (pre-contact trials -50 to -41), B (-40 to -31), C (-30 to -21), D (-20 to -11), E (-10 to -1), F (post-contact trials 1 to 10), G (11 to 20), and H (21 to 30). An ANOVA was used to examine the effect of trial group (eight levels) on lead and trail MFC, and Duncan's grouping was employed as a post hoc test.

3.5 Results

3.5.1 Toe versus Heel Clearances

In the lead limb trajectories of the successful trials, 62.6% of the minimum foot clearances (MFCs) were with the heel, indicating that the heel region of the foot came closer to the obstacle than the toe region in the majority of the successful trials. For the trail limb, 100% of the MFCs were with the toe.

3.5.2 Obstacle Contacts

Three subjects never contacted the obstacle, and 12 subjects contacted the obstacle one to four times, for a total of 24 contacts out of 3,843 trials, or 0.6%. All but two contacts were with the trail limb (92%). Three subjects had one obstacle contact, seven subjects had two contacts, one subject had three contacts, and one subject had four contacts. The first contact occurred with the trail limb for ten subjects, on average, at trial 103 (median 112) (Table 2). The first contact occurred with the lead limb for two subjects, at trials 52 and 87. All subsequent contacts were trail limb.

3.5.3 First Trail Limb Contacts for Ten Subjects

3.5.3.1 Cause of Contact

Subject 1 had a shorter horizontal distance (HD) in the contact trial, and the trajectory was the same size and shape as the preceding trials (note that the obstacle tipped when contacted, so the trajectory does not appear interrupted) (Figure 3). This behavior is consistent with trajectory C (top panel Figure 3). That is, if the subject maintained the same trajectory and foot placement had been shifted backwards about 100 mm, the toe would have cleared the obstacle. Therefore, the contact for subject 1 was the result of inappropriate foot placement. The remaining first trail limb contacts (90%) were classified as caused by inadequate toe elevation (see subjects 2, 3, 4, and 16, Figure 3). The MFC of the contact trial was only a few millimeters lower than the preceding successful trials for several subjects (e.g., subjects 2 and 3, Figure 3). When trail MFC was examined as a function of trial number (Fig. 2, right column), a progressive decrease was evident, which continued until obstacle contact occurred, followed by an increase in trail MFC (subjects 1, 5 and 9, Figure 4). Two subjects repeated this cycle within the data collection; subject 9 repeated the cycle three times (Figure 4), and subject 2 (not shown) repeated the cycle four times. Note that subject 1 had a shorter HD in the contact trial (Figure 3), but it appears that this subject would have hit the obstacle within the next few trials due to the decreasing trail MFC (Figure 4). The trail MFC at contact was within the detrended mean minus two standard deviations of the pre-contact epoch for 7 of the 10 subjects (70%).

3.5.3.2 Gait Characteristics in the Pre-contact Epoch

As noted earlier, one subject had 30 trials in the pre-contact epoch due to the first obstacle contact at trial 31 (see Table 2, and the number of subjects included in the group regression are at the top of each panel in Figure 5). For the individual regressions of trail MFC, nine subjects had a negative slope (average for ten subjects: -1.0 mm/trial), seven were significantly different from zero ($p < 0.01$, Table 2). This is also reflected in the group regression of trail MFC (-1.0 mm/trial, $p < 0.001$, Figure 5). The change of -1 mm/trial is about 1% of the trail MFC.

For the individual regressions of lead MFC, seven subjects had a negative slope (average for ten subjects: -0.4 mm/trial), four were significantly different from zero (Table 2). The change of –0.4 mm/trial is about 0.3% of the lead MFC. The negative slope is also reflected in the group regression of lead MFC, although the slope of the group regression was less steep (-0.2 mm/trial, $p = 0.006$, Figure 5). The individual regression slopes of the lead and trail MFC, -0.4 mm/trial and -1.0 mm/trial, respectively, were significantly different from each other as assessed with a paired t-test ($p = 0.01$).

For the individual regressions of trail HD, eight subjects had a negative slope, but none were significantly different from zero ($p > 0.02$). However, the group regression of trail HD had a significant slope of -0.4 mm/trial, $p = 0.003$ (Figure 5). For the individual regressions of gait speed, seven subjects had a positive slope, but only one was significantly different from zero ($p < 0.001$). However, when these individual changes were averaged, the group regression for gait speed was significantly different from zero

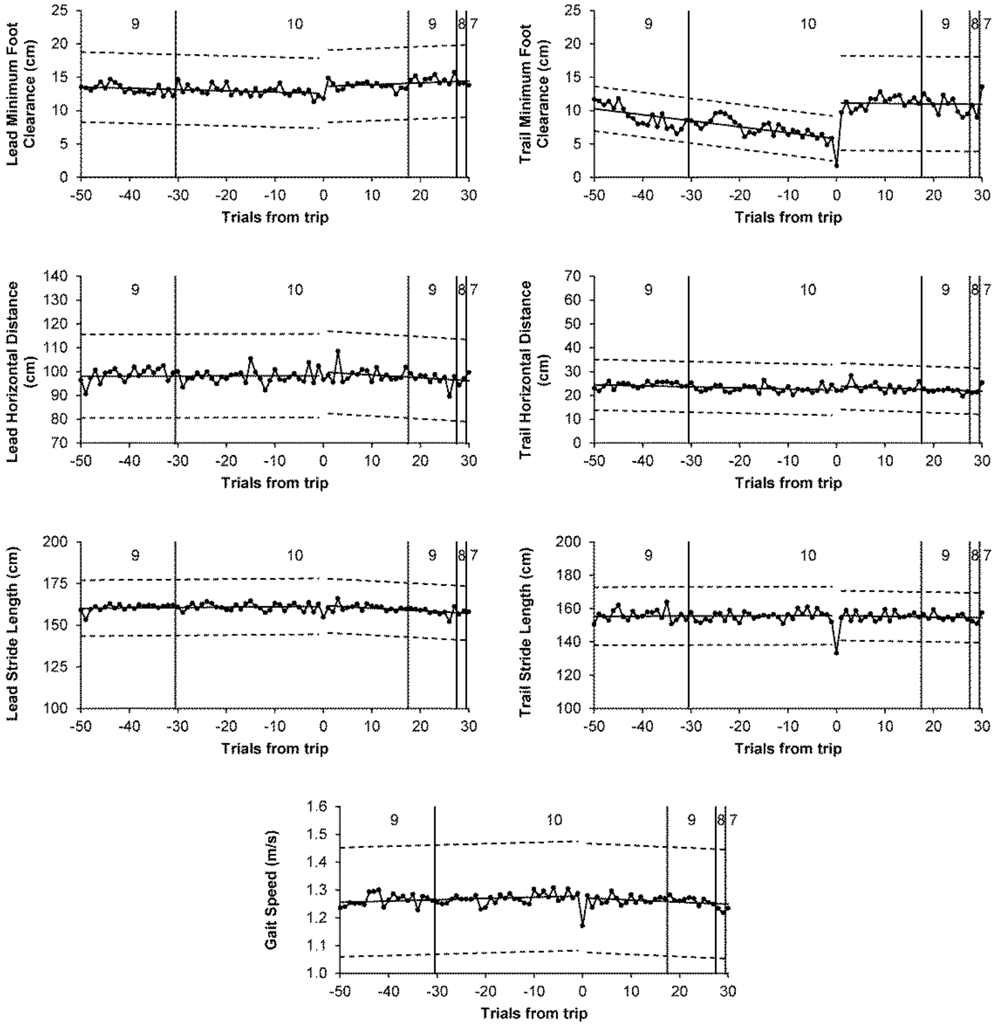

Figure 5 Dependent measures for lead (left column) and trail (right column) limbs as a function of trial number relative to the obstacle contact trial. Trial 0 corresponds to the obstacle contact. Minimum foot clearance (MFC) is shown in the top panel, horizontal distance is in the second panel, stride length is in the third panel, and gait speed is in the bottom panel. The measures were fit with a regression line (solid lines) for the pre-contact epoch (trial -50 to -1) and the post-contact epoch (trial 1–30). The dashed lines represent one standard deviation about the mean for the pre- and post-contact epochs. The numbers above indicate how many subjects were included in that portion of the figure.

with a positive slope of 0.0005 m/s (0.5 mm/s/trial) ($p = 0.01$). The change per trial is 0.04% of the average gait speed and is likely not functionally relevant. For the remaining variables (lead HD, lead and trail SL) during the pre-contact epoch, no consistent change was observed in the individual regressions. This lack of consistent change is also reflected in the group regressions for these measures ($p > 0.26$, Figure 5).

Since both trail MFC and trail HD decreased during the pre-contact epoch, it is important to consider if the closer foot placement resulted in the lower clearance. For example, as noted above in the contact trial of subject 1 (Figure 3), if foot placement had been shifted backwards about 100 mm, the toe would have cleared the obstacle without any other changes to the trajectory. However, only subject 1 demonstrated this behavior, so the majority of the contacts were due to inadequate foot elevation that was not a consequence of too-close foot placement.

3.5.3.3 Gait Characteristics in the Post-contact Epoch

As noted earlier, due to second obstacle contacts in the post-contact epoch, the length of the post-contact epoch ranged from 17 to 30 trials (see number of subjects included in the average at the top of each panel, Figure 5). For all gait variables during the post-contact epoch, no consistent pattern was observed for the slopes of the individual regressions. One group regression was significantly different from zero: lead SL slope -1.6 mm/trial ($p < 0.001$). The group regressions of the remaining variables were not significantly different from zero: lead MFC slope 0.3 mm/trial ($p = 0.07$), trail MFC slope -0.1 mm/trial ($p = 0.81$), lead HD slope -1.2 mm/trial ($p = 0.07$), trail HD slope -0.7 mm/trial ($p = 0.05$), trail SL slope -0.4 mm/trial ($p = 0.39$), and gait speed -0.001 m/s/trial ($p = 0.03$).

3.5.3.4 MFC Before and After the Contact Trial

Lead MFC did not change when examined as a function of trial group (p = 0.21). Since it appeared the first lead MFC following the contact trial might be different (Figure 5) and the difference might be masked by grouping 10 trials together, the single trial before and after contact for lead MFC were compared, and no difference was found (p = 0.31). Trail MFC changed as a function of trial group (p < 0.001), showing a decrease during the pre-contact epoch, followed by a higher, constant value in the post-contact epoch. Specifically, in the pre-contact epoch, group A (trials -50 to -41) was significantly higher than groups B–E (all remaining trials in pre-contact epoch), groups B, C, and D were not different from each other, and group E (trials -10 to -1) was different from groups A, B, and C (trials -50 to -21). All groups in the post-contact epoch (F, G, and H, trials 1–30) were not different from each other and were also not different from group A (pre-contact trials -50 to -40), but were different from all remaining groups (pre-contact trials -40 to -1). Trail MFC increased 75% in the 10 trials post-contact as compared to the 10 trials pre-contact.

3.5.3.5 Lead Limb Contacts for Two Subjects

The first obstacle contact for two subjects (6 and 12) was with the lead foot; both subjects subsequently contacted the obstacle with their trail foot (Figure 6, Figure 7). The rear region of the foot contacted the obstacle for subject 6. This is evident in the proximity of the toe versus heel trajectory to the obstacle (Figure 6). The contact in this trial appears to result from a longer lead HD, such that the heel came down too close to the obstacle before landing, as well as inadequate limb elevation (Figure 6). Subject 12 contacted the obstacle with the toe, and this trajectory does not appear to be different from the preceding 10 successful trials (Figure 6, Figure 7). Note that the lead MFC of the contact trial is higher than lead MFC for preceding successful trials (Figure 7); this likely resulted from the subject contacting the obstacle with the mid region of the foot (see Loverro et al., 2013), which was not instrumented in this study. For subject 12, it is interesting to note the variable placement of the lead foot before the obstacle, yet the trajectories of both the heel and toe converge just over the obstacle with minimal variability (Figure 6). There is no apparent effect of lead limb contact on either the ipsilateral or contralateral limb during subsequent trials (Figure 7). It is also interesting to note that the second contact for subject 6, a trail limb contact, apparently resulted from decreasing trail MFC until contact (Table 2, Figure 7).

3.5.4 Obstacle Contacts Subsequent to First Contact

The subsequent contacts are presented to provide a description of all contacts (Table 2). However, it is important to note that for most subsequent contacts, there is overlap between the epochs. For example, subject 1 contacted the obstacle at trials 141 and 159, and the epochs were shortened to account for the other contact as described above. However, the post-contact epoch of contact 1 and the pre-contact epoch of contact 2 include the same trials (trials 142–158). This is especially relevant because behavior was significantly impacted following the first contact (Figure 5). Nine of the fifteen subjects contacted the obstacle more than once, with 12 subsequent contacts. Two of the subsequent contacts were classified as inadequate foot placement (18%), and the remainder was classified as inadequate toe elevation. Three of the nine subjects (33%) had a trail MFC slope significantly different from zero preceding subsequent contacts (subjects 2, 3, and 9, Table 2; Figure 4), reflecting similar behavior as in the first contact.

3.5.5 Subjects Who Did Not Contact the Obstacle

Of the three subjects who did not contact the obstacle, it is apparent that subjects 13 and 17 would have ultimately contacted the obstacle with the trail foot if the data collection had continued (subject 13: slope -0.4 mm/trial, $R^2 = 0.54$, $p < 0.001$; subject 17: slope -0.5 mm/trial, $R^2 = 0.59$, $p < 0.001$, Figure 4). Subject 8 gradually shifted between increasing and decreasing trail MFC, with a sinusoidal-like cycle with a period of approximately 100 trials (Figure 4).

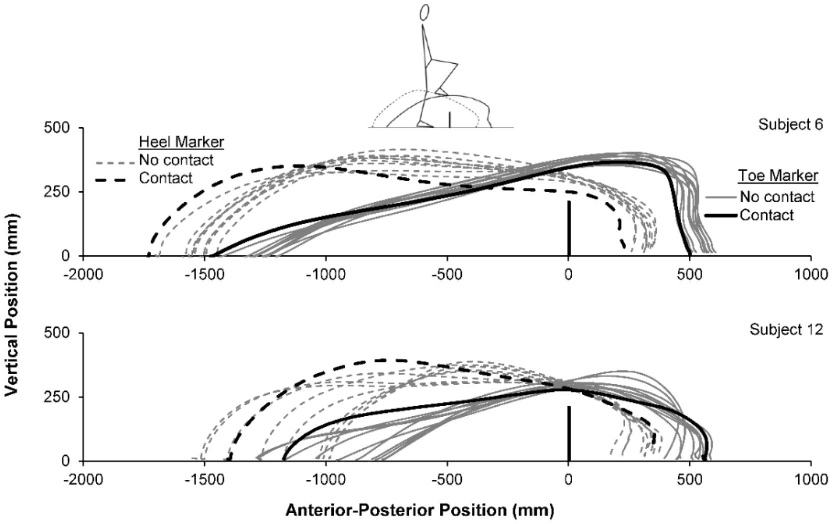

Figure 6 Lead limb trajectories of the toe (solid lines) and heel (dashed lines) for the two subjects with a lead limb contact. The black lines denote the obstacle contact trial, and the gray lines denote the preceding 10 successful trials. Subject 6 contacted the obstacle with the rear region of the foot, while subject 12 contacted the obstacle with the toe. The trajectory for the contact trial does not always go through the obstacle due to marker placement on the foot.

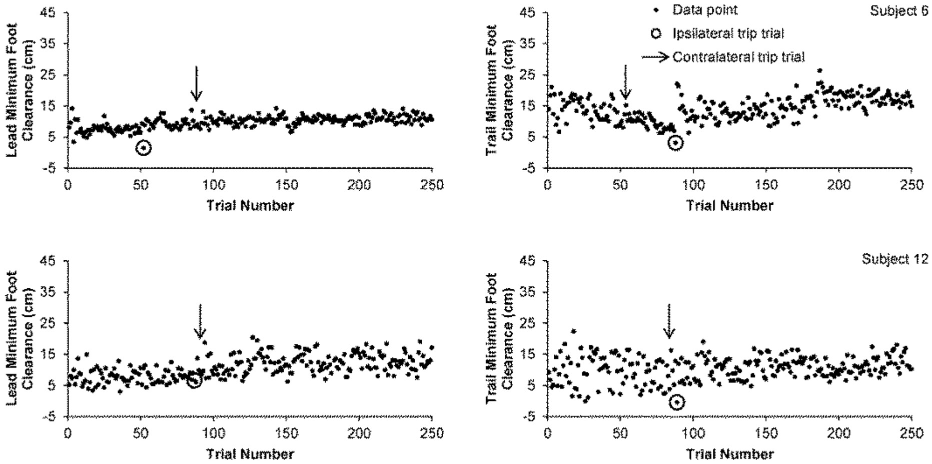

Figure 7 Minimum foot clearance (MFC) for the lead (left column) and trail (right column) limbs as a function of trial number for the two subjects that contacted the obstacle with the lead limb. The circled trials indicate the contact trials with the ipsilateral limb. The arrows indicate the corresponding MFC for the contralateral limb. Note that both subjects experienced a trail limb contact shortly after the lead limb contact.

3.6 Discussion

Suddenly appearing obstacles have provided a useful paradigm to understand balance recovery and falls (e.g., Brown et al., 2006; Eng et al., 1994; Weerdesteyn et al., 2004). However, it is also important to examine the behavior preceding a spontaneous contact with a fixed, visible obstacle. In this study, for 70% of subjects, the first obstacle contact was not the result of discrete, anomalous behavior on a single trial. Instead, a progressive decrease in trail MFC was observed, which continued until the obstacle was contacted with the trail foot. Decreased clearance during repeated obstacle crossing has been observed previously (Rhea et al., 2010), but the observation that MFC decreased until contact is surprising for two reasons. First, previous research with fixed obstacles found that inappropriate foot placement was the cause of failure, not inadequate foot elevation (Chou & Draganich, 1998; Patla & Greig, 2006). Second, it is typically argued that safety is paramount (e.g., Patla, Beuter, & Prentice, 1991) and decreasing MFC until contact is inconsistent with that argument. A number of possible explanations for the behavior are discussed. First, the contacts and behavior for lead versus trail limb are considered.

Obstacle contact occurred more frequently for the trail limb (92%), which is consistent with previous findings (trail limb contacts ranged from 67 to 100% of all contacts) with similar obstacles, in normal light, with either full vision or lower visual field obstruction (Mohagheghi et al., 2004; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). Under typical conditions, the trail limb is more likely to contact the obstacle due to the lack of visual feedback, the closer placement of the trail foot to the obstacle, and the short time available to flex the trailing limb adequately (Chou & Draganich, 1998). In addition, the vertical movement of the trail limb is faster than the lead limb during crossing (Heijnen et al., 2012b) which may make it more difficult to judge and/or correct the foot position relative to the obstacle. Conversely, lead limb contacts were more frequent than trail limb contacts under the following conditions: visual distortion through multifocal lenses (Johnson et al., 2007) and no vision during approach (Mohagheghi et al., 2004; Patla, 1998; Patla & Greig, 2006). The lead limb is visually guided during crossing (e.g., Patla, 1998); therefore, it is not surprising that visual manipulations are more likely to affect the lead limb trajectory. The trail limb trajectory is guided by a neural representation of obstacle properties, but it is important to note that vision is used to establish this representation (Lajoie et al., 2012). Therefore, the trail limb trajectory should also experience an increased number of contacts. However, in these studies, less contacts are observed for the trail limb because if the lead limb fails, the success or failure of the trail limb cannot be assessed.

Lower contact rates for the lead limb may also reflect greater caution during lead limb crossing, as these contacts are more threatening to stability. The lead foot is moving forward and downward at obstacle crossing (Patla et al., 1996, also see heel trajectory, Figure 6), decreasing the ability to lift the limb to establish a new, larger base of support. At the same time, the center of mass is moving away from the stance foot, reducing the available time to recover. Conversely, the trail foot at crossing is moving forward and upward, increasing the ability to lift the limb to establish the new base of support, and the center of mass is moving toward the stance foot, decreasing the threat to balance.

The heel region of the lead foot was closer to the obstacle than the toe region in 63% of the trials. Loverro et al. (2013) also observed the majority of lead MFCs were in the rear foot region in young, healthy subjects, so it seems reasonable to conclude that most lead contacts would occur with the rear region of the foot. However, only two lead contacts were observed, one with the rear region of the foot and one with the mid region, which is not enough observations to indicate if fore, mid, or rear foot contacts are more likely in young, healthy subjects. The MFC for the trail limb was always with the toe, and all trail limb contacts occurred with the forefoot region, as predicted by Patla et al. (1996).

The results of this study also support the concept of limb independence during adaptive gait, consistent with a growing body of literature (Anstis, 1995; Lajoie et al., 2012; Niang

& McFadyen, 2004; Patla et al., 1996; Rhea & Rietdyk, 2011; Yang et al., 2004). Limb independence is the idea that the motion and/or feedback of one limb are not used to control the contralateral limb. Although both lead and trail MFC showed a significant downward slope during the pre-contact epoch, trail MFC decreased significantly faster than lead MFC. In addition, contact with the trail limb increased the subsequent trail limb clearance by 75%, but lead limb clearance did not change. These findings are consistent with observations of a smaller number of spontaneous contacts for a smaller obstacle (10 cm) when the lower visual field was obstructed; trail clearance increased 41%, but lead clearance did not change (Rhea & Rietdyk, 2011). In that study, only eight trials after contact were available for analysis, and trail toe clearance remained high for the eight trials. The results reported here indicate that the trail limb behavior change lasted at least up to 30 trials for the majority of subjects. When subjects contacted an obstacle due to visual distortion from prisms, a large overcompensation in lead toe clearance was also noted in subsequent trials, but the paper does not indicate lead or trail contact (M. S. Alexander et al., 2011).

It is apparent that limb elevation was higher than necessary in the first trials, since the MFC decreased over 103 trials, on average, before obstacle contact occurred. The early exaggerated behavior was likely the consequence of caution, ensuring that adequate elevation was achieved. However, this requires more energy and is unlikely to be sustained indefinitely in young, healthy subjects. The progressive decrease is consistent with a continuous process, while a steplike transition indicates a discrete process occurred. Possible causes of continuous and discrete processes include fatigue and inattention, respectively; these factors and others will be considered in more detail later.

Thirty percent of the first trail contacts occurred due to a discrete anomalous occurrence of either inadequate foot elevation (20%) or too-close trail foot placement (10%), likely due to inattention on a single trial. The remaining 70% of the first trail contacts were due to a progressive decrease in MFC until the foot contacted the obstacle. This progressive decrease was also observed in two of the three subjects who did not trip; they apparently would have contacted the obstacle if data collection had continued (e.g., subject 17, Figure 4). Three of nine subjects demonstrated a progressive decrease in contacts subsequent to the first contact. Therefore, the progressive decrease behavior appears robust. The design of this study did not allow us to address why MFC progressively decreased, but possible explanations are considered next.

Fatigue may have led to the decreased elevation, due to walking for up to 100 min. To reduce the impact of fatigue, subjects paused briefly between trials and sat down for 2 min every 50 trials, but this may not have eliminated fatigue. If the progressive decrease was due to fatigue, the trail limb apparently fatigued faster than the lead limb due to the significantly steeper slope of trail MFC. In support of this concept, higher knee power generation was observed in the trail limb relative to the lead limb during obstacle crossing (Niang & McFadyen, 2004). However, the first contact occurred at trial 31 and on average at trial 103 (approximately 10 and 34 min, respectively). In comparison, during continuous walking over level ground for 3 h, subjective fatigue was first observed at 60 min (rating of perceived exertion) and objective fatigue at 105 min (mean power frequency of tibialis anterior) (Yoshino, Motoshige, Araki, & Matsuoka, 2004). If contacts were due to fatigue, one would predict that contacts would occur more frequently as the data collection progressed. On average, there were 103 successful trials before the first contact, 98 successful trials after the first trail limb contact, and 104 successful trials after the second trail limb contact (trials were counted from the preceding trail limb contact to the following trail limb contact, or to end of data collection, whichever occurred first). Therefore, there was no evidence of more frequent contacts over time. In addition, gait speed did not decrease in the pre-contact epoch (Figure 5). Therefore, the observations do not support fatigue as a plausible explanation for decreased MFC and obstacle contact.

A strategy to minimize energy would result in decreased MFC. However, if obstacle contact arrested the forward limb movement, the energy associated with recovery would be greater than the energy to lift the limb higher, and energy minimization would ultimately be counterproductive. In addition, safety would be compromised, which is typically regarded as paramount (e.g., Patla, 1991). In this study, energy minimization may have been prioritized over safety as the collapsible obstacle did not threaten stability. However, the observation that trail MFC increased 75% and remained high following contact is inconsistent with prioritization of energy minimization over safety. In addition, it is unclear why a progressive decrease was adopted, as more energy would be conserved earlier with a discrete transition to a lower MFC.

Boredom and/or inattention may also have led to decreased MFC. The contact may have startled the participant and increased attention in the following trials. However, boredom and inattention are more likely to be discrete processes, as opposed to continuous. The effect of boredom and/or inattention cannot be discounted, especially since the same obstacle was used, but inattention may also occur in the ‘real’ world when stepping up onto curbs multiple times each day.

The following possibility is more speculative. The continued decrease in trail MFC until contact occurred could be interpreted as inaccurate knowledge of trail foot position relative to the obstacle. The trail limb is not visible, and there are 12 major joint angular degrees of freedom (DOF) between the stance foot and crossing foot (Winter, 1991). The DOF may have been gradually adjusted in a continuous process to gain sensory information by ‘exploring’ the region above the obstacle, continuing in some cases until the obstacle is ‘found’ due to contact. This idea emerges from the ecological approach to perception (Gibson, 1979) and has been supported by experimental findings in postural control (Claxton, Melzer, Ryu, & Haddad, 2012; Haddad, Ryu, Seaman, & Ponto, 2010; Riccio, 1993; Van Emmerik & Van Wegen, 2002). This idea is supported by the observation that none of the subjects exhibited steady state behavior of the trail MFC before first contact (Figure 4). It is noted that the three subjects that demonstrated decreased trail MFC after the first trail contact do not support this argument, as they apparently did not ‘learn’ the necessary foot elevation. However, for the majority of subjects, trail MFC remained high in subsequent trials to clear the obstacle.

Therefore, there are a number of possibilities for the observed behavior of decreased MFC until contact. We note that these possible causes are not mutually exclusive, and the cause may be a combination of factors dependent on the subject and/or the context. For example, the pre-contact decrease in trail MFC may have been due to energy minimization, and the higher MFC following contact may be due to the participant's perception that they 'failed' in front of the experimenters. Hypotheses regarding the cause of decreased MFC can be developed and tested. For example, if inattention led to the decrease in MFC, a concurrent secondary task would result in faster rates of decrease and/or increased contacts. However, the variability of the progressive decrease (range of slope: 0.4 to -4.6 mm/trial, Table 2) will compromise statistical power when comparing across conditions. Future research should also examine changes at the ankles, knees, hips, and trunk, to determine if there is a progressive change in one DOF or if multiple DOF are modified to create the observed change in foot clearance. This data may also determine if one or more DOF are mostly responsible for spontaneous contacts. Finally, we acknowledge that the progressive decrease in foot clearance may have been induced by observation in a laboratory setting; it is unknown if this is a natural behavior.

In summary, the main cause of spontaneous contacts with a fixed, visible obstacle was a progressive decrease in foot clearance until contact occurred. The possibility that this behavior is voluntary (although unconscious) is a new and different perspective on obstacle crossing behavior. This is an interesting paradigm that may provide insight when examined in populations with higher fall rates, such as frail older adults, people with Parkinson's disease, stroke, or other disabilities.

CHAPTER 4. INTERMISSION I: FROM ONE EXTREME TO THE OTHER

In the previous chapter, we examined failures in adaptive locomotion without any manipulations of vision or instructions. In other words, behavior was examined under conditions that are more representative of everyday life. Several factors were established. First, failure rates when crossing a stationary, visible obstacle were 1%. This is similar to the 1-2% reported by other research groups (Berard & Vallis, 2006; Mohagheghi et al., 2004; Muir et al., 2015; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006). Second, the majority of failures (92%) occurred with the trail limb, which is consistent with previous literature as well (Berard & Vallis, 2006; Mohagheghi et al., 2004; Muir et al., 2015; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006). Third, when examining the cause of failures, it was clear that the majority of trail limb contacts (90%) were due to inadequate foot elevation, not incorrect foot placement as previously reported (Chou & Draganich, 1998; Patla & Greig, 2006). The main difference between the latter two studies and Chapter 3 is that failures were induced in the latter two studies by manipulating vision or instructions. Finally, when closer examining the foot elevation, a progressive decrease (or drift) was observed in foot clearance values, in particular for the trail limb. This drift in trail foot clearance was the cause of contact in 70% of the failures. The remaining failures were due to an anomalous decrease in foot elevation (20%) or incorrect foot placement (10%). This final observation regarding the drift in trail foot clearance indicates that the obstacle memory established from feedforward visual information for trail limb guidance is inferior relative to the combination of feedforward and online information available to the lead limb.

As mentioned previously, Study 1 examined failures in adaptive locomotion in an optimal condition without any manipulations of vision or instructions. The next study will look at the other extreme. Online obstacle position information will be provided, but feedforward obstacle height information gathered during the approach phase, and somatosensory information regarding obstacle contact will not be available for either limb in order to examine to role of an obstacle memory. Participants will need to use an obstacle height memory for both lead and trail limbs to successfully cross the obstacle. The next study will determine whether an obstacle height memory can accurately guide the foot over an obstacle when online position information is available.

CHAPTER 5. MEMORY-GUIDED OBSTACLE CROSSING: MORE FAILURES WERE OBSERVED FOR THE TRAIL LIMB VERSUS THE LEAD LIMB

This study has already been completed and published in Experimental Brain Research (Heijnen et al., 2014). The full text is reprinted below with permission from Springer, provided by the Copyright Clearance Center.

5.1 Specific Aim

To determine the role of visual information to accurately guide the lower limb trajectory over an obstacle in healthy young adults; in particular, whether feedforward height information can accurately guide the foot over an obstacle when online position information is always available.

5.2 Abstract

During adaptive locomotion, vision is used to guide the lead limb; however, the individual must rely on knowledge of obstacle height and position, termed obstacle memory, to guide the trail limb. Previous research has demonstrated that visual sampling of the obstacle during approach was adequate to provide obstacle height information, but online visual update of distance to the obstacle was required to plan and implement appropriate foot placement. Our purpose was to determine whether obstacle height memory, coupled with a visible obstacle position cue, could successfully guide the foot

during obstacle crossing. Subjects first stepped over an obstacle for 25 trials; then, the obstacle was removed, but its position was marked with high-contrast tape; subjects were instructed to step over the obstacle as if it was still there (termed “virtual obstacle”) for 25 trials. No changes in foot placement were observed; therefore, the position cue provided salient online information to guide foot placement. Average failure rates (subject would have contacted the virtual obstacle if it was present) were 9 and 47 % (lead and trail limb, respectively). Therefore, action was impaired for both limbs when guided by obstacle height memory, but action was impaired to a greater extent for the trail limb. Therefore, viewing the obstacle during approach appears to facilitate the memory needed to guide obstacle crossing, particularly for the trail limb. This is likely because the lead limb is visible in the peripheral visual field during crossing, but the trail limb is not.

5.3 Introduction

It is well recognized that locomotor tasks are completed under continuous control based on visual information (e.g., Lee, Lishman, & Thomson, 1982; Patla, 1998). When stepping over an obstacle, the first limb (leading limb) is visible in the lower visual field, and online visual information is used to control the lead limb trajectory (Mohagheghi et al., 2004; Patla, 1998; Patla et al., 1996; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). However, when the trailing limb clears the obstacle, the limb and the obstacle are not visible, so the individual must rely on knowledge of obstacle characteristics to control the trail limb trajectory. These characteristics likely include spatial characteristics, such as height, position, and depth (Patla & Rietdyk, 1993), and perceived characteristics, such as fragility (Patla et al., 1996). This visuospatial knowledge has been termed as “stored obstacle representation” (Lajoie et al., 2012) or an “obstacle memory” (McVea & Pearson, 2006, 2007; Shinya et al., 2012; Whishaw et al., 2009).

The concept that a representation is used to guide motor output is controversial, especially when vision is available (e.g., Anson, Burgess, & Scott, 2010; Warren, 2006). However, when vision is not available, retained knowledge of spatial characteristics of a target is used to control upper limb reaching tasks (Binsted, Rolheiser, & Chua, 2006; Heath, Neely, Krigolson, Binsted, & Elliott, 2010; Milner, Dijkerman, McIntosh, Rossetti, & Pisella, 2003). Similarly, in locomotor research, it has been demonstrated that quadrupeds retain obstacle characteristics for long period of time. In one set of studies, cats stepped over an obstacle with the forelimbs and paused to eat; during the pause, the obstacle was lowered. When gait resumed, the hind limb trajectories clearly demonstrated that the cat remembered the obstacle and modified the trajectory based on the obstacle size and position (McVea & Pearson, 2006, 2007). similar findings were observed in horses (Whishaw et al., 2009). In humans, Lajoie et al. (2012) demonstrated that the trail leg trajectory was scaled appropriately to obstacle height after straddling an obstacle for up to 2 min. In the preceding studies, the obstacle was visible prior to and during lead limb crossing, which may have helped establish the memory. However, participants also successfully crossed obstacles when an obstacle was viewed during approach and when vision was removed during the last three steps before obstacle crossing (Mohagheghi et al., 2004). When vision was removed earlier (five steps before obstacle crossing), subjects were only 50% successful (Patla & Greig, 2006). In the latter study, the main cause of failure was not inappropriate limb elevation, but rather incorrect foot placement. the authors concluded that while initial visual sampling was adequate to provide obstacle height information, online visual update of distance to the obstacle was required to plan and implement appropriate foot placement. Our goal was to extend this line of research to determine whether action can be accurately guided by an obstacle memory when online visual distance to the obstacle was available.

In the present study, subjects were instructed to step over an obstacle that was not physically present (termed a virtual obstacle), in the same manner as upper limb aiming paradigms where the target is initially visible, but is not visible during the aiming movement (Binsted & Heath, 2005; D. Elliott, 1988; Heath, 2005). Subjects stepped over an actual obstacle 25 times (epoch 1) before they stepped over the virtual obstacle 25 times (epoch 2). Obstacle clearance performance was quantified at two levels: (1) whether the subject would have contacted the virtual obstacle if it had been present and (2) differences in trajectory characteristics when crossing a real versus virtual obstacle. The average obstacle contact rate is about 1–2% in young, healthy subjects in a research setting (Berard & Vallis, 2006; Heijnen et al., 2012a; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), so we quantified successful performance as a virtual obstacle contact rate of 5% or less. Given the empirical support for long-lasting obstacle memories, the hypotheses were developed in support of the obstacle memory successfully guiding action. We hypothesized that (1) subjects would successfully clear the virtual obstacle at least 95% of the time and (2) trajectory characteristics would be similar for the real and virtual obstacles. Further, we hypothesized that failure rate and trajectory characteristics would not change during the course of epoch 2. This would demonstrate that the obstacle memory did not decay over the 9-min epoch.

After 19 subjects were collected, it was noted that the trail limb failure rate (47%) was about four times greater than the lead limb failure rate (9%). therefore, we added a condition to the following 21 subjects to determine whether the high trail limb failure rate was due to inadequate instructions for the trail limb. We found that trail limb failure remained higher than lead limb failure. As the failure rate was substantially larger than hypothesized, we also completed a second study to determine whether subjects would scale the trajectories to different heights of virtual obstacles. We found that subjects scaled the lead and trail limb trajectories to the virtual obstacle height, confirming that an obstacle memory was being used to guide the trajectory despite high failure rates.

5.4 Methods

5.4.1 Experiment 1

Forty-one subjects were recruited from a university population, and two were excluded due to data collection problems, resulting in 39 total subjects (22.1 ± 2.4 years, 18 males). Subjects were free from any impediments to normal locomotion, as verified by self-report. All subjects signed a consent form approved by the local institutional review board. Subjects were instrumented with eight infra-red emitting diodes (IREDs). Six IREDs were placed on the lateral aspect of the left foot at the distal phalanx of the third toe, calcaneus, and malleolus and on the medial aspect of the right foot at the distal phalanx of the first toe, calcaneus, and malleolus. Two IREDs were placed on the lateral side of the head. One IRED was placed on the lateral side of the obstacle. two Optotrak 3020 sensors (NDI, Canada) recorded the position data of the IREDs at 60 Hz. The obstacle was composed of masonite (painted flat black) with two supports (L-brackets) mounted on the leading face of the obstacle, such that if the subject contacted the obstacle, it would fall forward without arresting the swing limb. The obstacle was 100 cm wide by 0.3 cm deep, and the height was 25% of the subject’s leg length (range 19.5–26.0 cm in 0.5 cm increments). For each subject, before the experiment began, the starting position was adjusted such that the right foot was naturally the lead foot (first foot to cross obstacle). The right limb was set as the lead foot because we have previously observed that when subjects self-select the lead limb, occasionally a subject will switch between right and left as the lead limb; these intermixed trajectories were qualitatively different for some subjects (unpublished observations). These differences would have confounded the comparison across real and virtual obstacles if the subject used different lead limbs for the real and virtual obstacles; thus, we used the right limb as the lead limb to eliminate this confound. After the starting position was determined, subjects were instructed to always cross the obstacle with the right foot first. The obstacle position was marked with masking tape (100 cm long). Two obstacle conditions were observed as follows: the obstacle was in place (real obstacle) or the obstacle was not in place (“virtual obstacle” located at masking tape).

Before data collection, subjects were instructed as follows: “the obstacle will be in place for the first 25 trials and will be removed for next 25 trials. When the obstacle is not there, you will be asked to step over the tape as if the obstacle was still there.” In the first 25 trials (epoch 1), subjects walked down an 8-m walkway at a self-selected pace, stepped over the obstacle in the middle of the walkway, and continued walking. The obstacle was removed in the second epoch of 25 trials, but the obstacle position tape remained (epoch 2). At the beginning of epoch 2, subjects were instructed “step over the piece of tape as if the obstacle was still in place and cross the obstacle with your right leg first.” the obstacle was returned to the walkway for the third epoch of 25 trials (epoch 3). Epoch 3 was used to ensure that any changes across real and virtual trajectories (epochs 1 and 2) were not a simple adaptation due to repeated crossings (Heijnen et al., 2012a; Rhea et al., 2010). A fourth 25-trial epoch was added for the latter 21 subjects to investigate the influence of instruction on the dependent variables (epoch 4). The obstacle was removed in epoch 4 as in epoch 2, and subjects were instructed “step over the piece of tape as if the obstacle was still in place. Make sure that you cross the obstacle with your right leg first and remember to also step over the obstacle with the left leg.”

Data were analyzed with MATLAB 2010a software (MathWorks Inc., MA, USA). Data were filtered off-line at 8 Hz with a fourth-order zero-phase-shift low-pass Butterworth digital filter (Winter, 2009). Dependent variables were minimum foot clearance (MFC), toe peak elevation, toe peak position relative to the obstacle, horizontal distance, stride length (SL), and failure rate. Variability measures were calculated as the standard deviation. High limb velocity during crossing can compromise clearance accuracy (up to 17% error), so spatial resolution was increased with a cubic interpolation algorithm (Heijnen et al., 2012b). Failure could result from either the forefoot or rearfoot region of the foot passing through the obstacle (Chen, Ashton-Miller, Alexander, & Schultz, 1991;

Heijnen et al., 2012a; Loverro et al., 2013; Telonio, Blanchet, Maganaris, Baltzopoulos, & McFadyen, 2013; Thies et al., 2011). Therefore, both toe and heel clearances were calculated: toe/heel clearance was the vertical distance between the IREDs on the toe/heel and obstacle as the toe/heel crossed the obstacle. The minimum of the toe and heel clearance for each trial was quantified as MFC. A negative MFC indicated failure; failure magnitude was quantified as the average of the negative MFC. Toe peak was the maximum vertical distance between the toe and the ground. Toe peak position was the anterior–posterior distance of the IREDs on the toe relative to the obstacle at toe peak. A negative value indicated that toe peak occurred before the toe crossed the obstacle (e.g., subject 19, virtual obstacle trajectories of lead limb, Figure 8), and a positive value indicated that toe peak occurred after the toe crossed the obstacle. Horizontal distance was calculated as the anterior–posterior distance between the IREDs on the toe and obstacle at toe-off. SL was calculated as the anterior–posterior distance between the toe marker at toe-off and the subsequent toe-off of the same limb. Overall failure rate was calculated as the percentage of obstacle contacts if the obstacle had been in place in the virtual obstacle condition; failure was determined for the lead and trail limbs separately. Subjects were classified as successful, achieving a failure rate of 5% or less, or not successful. If the obstacle memory degraded during epoch 2, we would expect the failure rate and MFC to change. To quantify this, trial-specific failure rate was calculated as the percent of subjects who failed in each of the trials in epoch 2 and a linear regression was performed. Further, a linear regression of MFC for all trials in epoch 2 was calculated for each subject individually. All variables were calculated for both the lead and the trail limb.

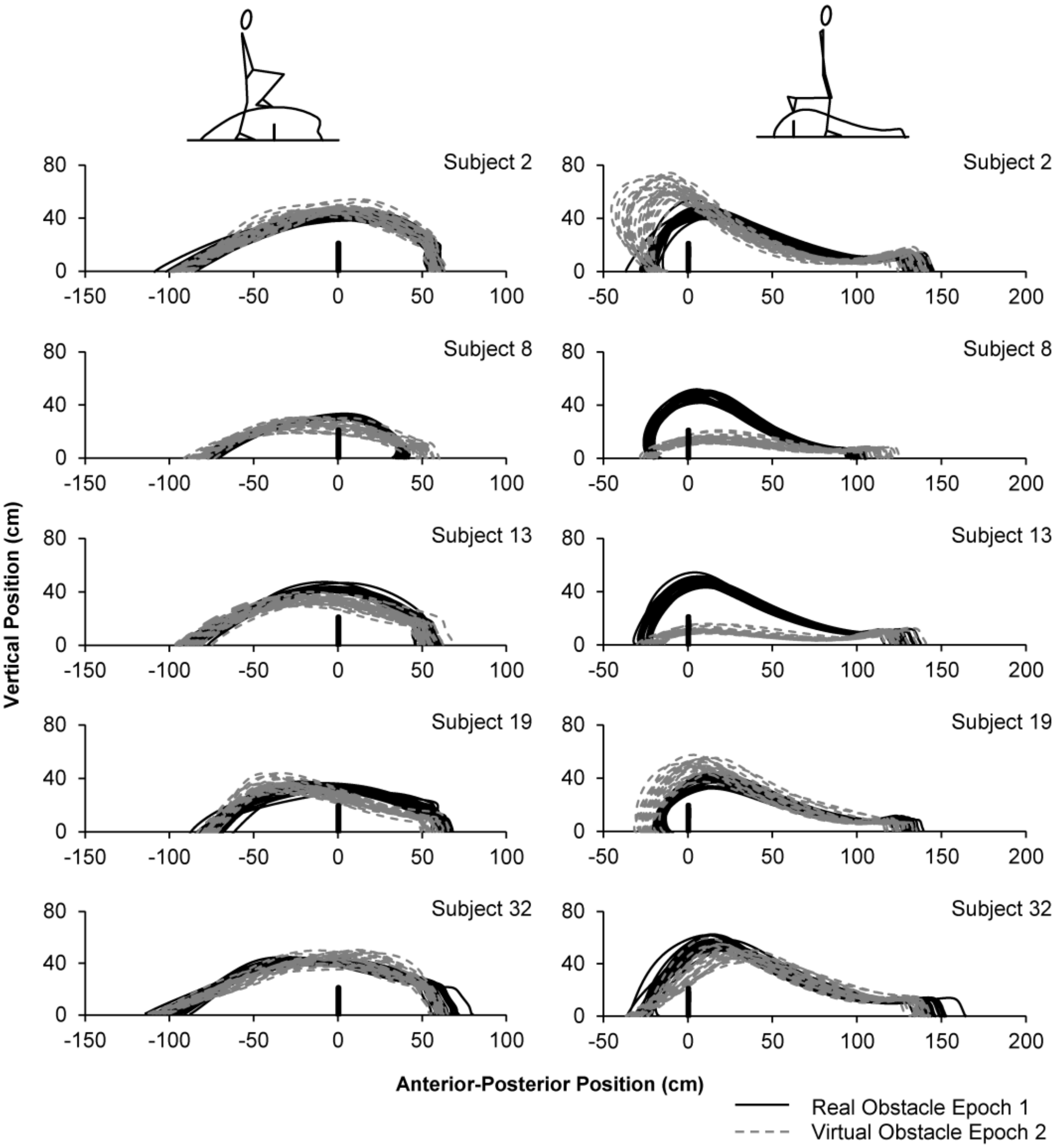

Figure 8 Toe trajectories of the lead (left panel) and trail limb (right panel) for five subjects. Subjects stepped over a real obstacle in epoch 1 (black lines) and crossed a “virtual” obstacle in epoch 2 (gray dashed lines).

5.4.2 Experiment 2

Twenty-four subjects were recruited from a university population (20.2 ± 0.9 years, 8 males). Subjects were free from any impediments to normal locomotion, as verified by self-report. All subjects signed a consent form approved by the local institutional review board. Instrumentation and methods were identical to Experiment 1 with the following exceptions: two obstacle heights were examined, 15 and 25 cm. the obstacles were presented in a blocked manner, with order of presentation counterbalanced. For example, when the small obstacle was presented first, epochs 1–4 were as follows: real 15 cm, virtual 15 cm, real 25 cm, and virtual 25 cm, respectively. Toe peak was compared between the 15- and 25-cm virtual obstacles.

5.4.2.1 Rationale for Using Real and Virtual Obstacles in a Series of Epochs

The virtual obstacle approach was adapted from the common experimental paradigm to examine visual control of reaching: the target is initially visible but disappears before the target is reached (Binsted & Heath, 2005; D. Elliott, 1988; Heath, 2005; Milner et al., 2003). In the same manner, subjects here were instructed to step over an obstacle that was not physically present. This preserved vision of the environment and allowed the examination of memory-guided action for both the lead and trail limbs. To create the obstacle memory, the subject could simply have been shown the actual obstacle. However, walking upstairs facilitated the stair height memory compared to when information was obtained by vision alone (Shinya et al., 2012). Therefore, to increase the likelihood of generating a robust memory, subjects stepped over an actual obstacle 25 times (epoch 1) before they stepped over the virtual obstacle 25 times (epoch 2). The 25 trials in epoch 2 also allowed us to examine whether the memory degraded over time, as it takes about 9 min to collect 25 trials in young healthy adults.

A within-subject ANOVA was used to examine the effect of epoch (four levels) on each dependent variable. A generalized linear mixed model was used to allow the residuals to vary (GLIMMIX in SAS 9.3, Cary, NC, USA). Due to the large number of dependent variables, the p value was set to 0.01. Tukey–Kramer post hoc analyses were used to determine whether behavior changed due to repeated exposures within the real obstacle condition (epoch 1 vs 3), to determine whether behavior changed for real versus virtual obstacles (epoch 1 vs 2), and to determine whether toe peak changed for the virtual 25-cm obstacle versus the virtual 15-cm obstacle (Experiment 2). A generalized linear mixed model was used to test for differences in failure rate.

5.5 Results

5.5.1 Experiment 1

5.5.1.1 Contacts with the Real Obstacle

Ten contacts with the real obstacle were observed in nine subjects, for a contact rate of 0.5%. Ninety percent of the contacts were with the trail limb. A large increase in toe clearance has been observed in subsequent trials after obstacle contact (M. S. Alexander et al., 2011; Heijnen et al., 2012a; Rhea & Rietdyk, 2011), so these nine subjects were excluded from further analyses to ensure that any changes in clearance were due to the independent variable manipulation, and not in response to the contact. The remaining 30 subjects were included in further analyses, 15 have observations in epochs 1–3, and the remaining 15 have observations in epochs 1–4.

5.5.1.2 Qualitative Comparisons of Real and Virtual Trajectories

Lead toe trajectories for the real and virtual obstacles were similar, but a generally lower elevation and an earlier peak are noted in most subjects (Figure 8, right panel, subjects 8, 13, and 19). Failures are demonstrated by the trajectory passing through the obstacle (e.g., subject 8); note that failures also resulted from the heel trajectory passing through the obstacle (not shown). Marked differences in the trail limb trajectories were readily apparent, with high intersubject variability (Figure 8, right panel). Subjects 8 and 13 demonstrate large undershoot, and subjects 2 and 19 demonstrate large overshoot, with subject 2 pulling the limb backwards. When subjects were given further instruction with the trail limb, some subjects improved (e.g., subject 22, Figure 9, right panel), but the majority demonstrated the same general trajectories with the virtual obstacle (e.g., subjects 24 and 41, Figure 9).

5.5.1.3 Failure Rate with the Virtual Obstacle

Overall failure rates with the virtual obstacle (epoch 2) were 9 and 47%, for the lead and trail limb, respectively (Table 3; Figure 8). therefore, hypothesis 1, that subjects would successfully clear the virtual obstacle at least 95% of the time, was rejected for both the lead and trail limb. The failure rate was significantly higher for the trail limb versus the lead limb ($p < 0.001$). Trial-specific failures did not change during epoch 2 for the lead limb, but trail failure increased 10% in a linear fashion during epoch 2 ($p = 0.001$; Figure 10). Failures during epoch 2 were examined for individual subjects, and it was observed that the subjects who were initially successful tended to remain successful and subjects who were initially unsuccessful tended to remain unsuccessful; therefore, these two groups did not affect the failure rate. however, there were four subjects (13%) who changed from unsuccessful to successful during epoch 2, and these four subjects were responsible for the change in average trail trial-specific failure. therefore, although the significant increase in trail failure during epoch 2 appears to indicate memory decay, it was being driven by only 13% of the subjects.

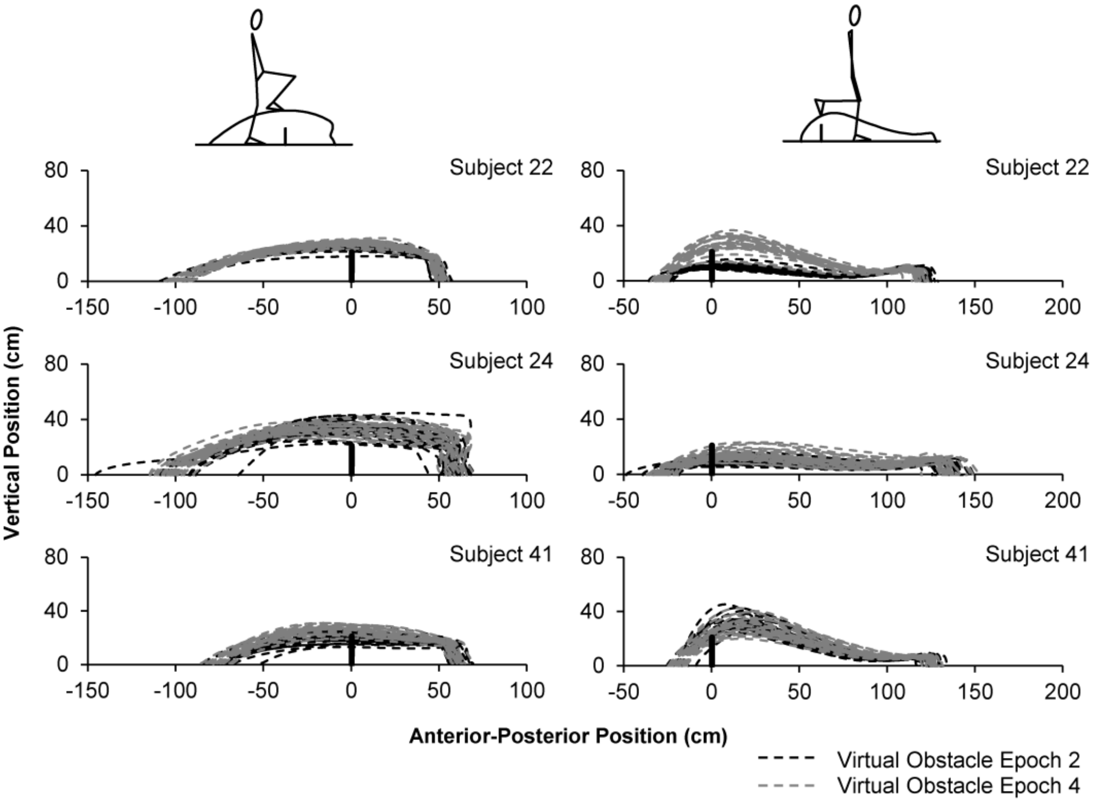

Figure 9 Toe trajectories of the lead (left panel) and trail limb (right panel) for three subjects. Subjects stepped over a “virtual” obstacle in epoch 2 (black dashed lines) and epoch 4 (gray dashed lines); in epoch 4, subjects received more instruction than in epoch 2.

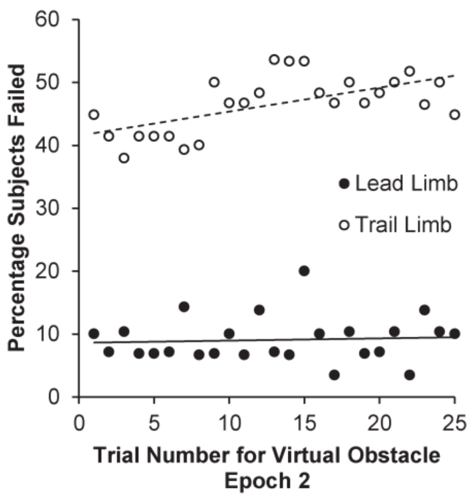

Figure 10 Failure rate calculated for each trial during epoch 2 (virtual obstacle). Closed circles represent percent of subjects who failed with the lead limb, and open circles represent percent of subjects who failed with the trail limb. Failures did not change for the lead limb during the epoch, but trail failure significantly increased (p = 0.001).

5.5.1.4 Classification of Successful and Unsuccessful Subjects

Nineteen subjects (63%) were classified as lead limb successful (achieved a lead failure rate of 5% or less in epoch 2 (e.g., subjects 2, 13 & 32 Figure 8), and 11 (46%) were classified as lead limb unsuccessful (e.g., subject 8, 19 Figure 8; Table 3). thirteen subjects (43%) were classified as trail limb successful (e.g., subjects 2, 19 & 32 Figure 8; Table 3), and 17 (67%) were classified as trail limb unsuccessful (e.g., subjects 8 & 13 Figure 8). ten subjects (33%) were classified as successful with both the lead and trail limb (e.g., subjects 2 & 32 in Figure 8; Table 3). For those subjects with failed trials, the average magnitude of the failure was 1.7 ± 1.0 and 8.4 ± 2.4 cm for the lead and trail limb, respectively.

Table 3 Individual subject failure rates for the virtual obstacle during epochs 2 and 4 for the lead and trail limbs.

	Epoch 2	
Subj	**Lead %**	**Trail %**
2	0	0
3	0	0
4	0	100
5	0	4
6	16	84
8	16	100
9	0	100
10	0	64
11	0	0
12	12	0
13	0	100
14	0	0
16	0	0
17	0	0
19	17	0

	Epoch 2		**Epoch 4**	
Subj	**Lead %**	**Trail %**	**Lead %**	**Trail %**
20	8	100	0	100
21	8	16	12	8
22	12	100	16	16
23	44	100	50	100
24	4	100	0	96
25	71	100	20	100
26	0	16	0	0
31	0	0	0	0
32	0	0	0	0
33	16	60	4	0
37	0	77	0	93
38	0	83	0	56
39	0	100	4	100
40	0	0	0	0
41	46	4	4	24

5.5.1.5 Failure Rate as a Function of Instruction

This analysis included only the latter 15 subjects with observations in epochs 2 and 4, so epoch 2 average failure rates are slightly different from those reported above for all 30 subjects. Lead limb failure rate decreased from 14 to 7% from epochs 2 to 4, respectively ($p = 0.004$; Table 3; Figure 9). Trail limb failure rate decreased from 57 to 47% from epochs 2 to 4, respectively ($p < 0.001$). Therefore, hypothesis 4, that trail limb failure rate will decrease with more specific instruction, was accepted. However, lead limb failure rate also decreased to a similar extent. Note the high variability in the improvement: trail limb failure rate improved more than 20% with instruction for three subjects (subjects 22, 23, and 38 improved 84, 60, and 27%, respectively), but subject 41 had 20% higher failure (Table 3; Figure 9).

5.5.1.6 Change in Minimum Foot Clearance During Epoch 2

There was no change in lead MFC for the majority of the subjects (80%) during epoch 2. Of the six subjects (20%) with slopes that were significantly different from zero in epoch 2, MFC increased for four subjects and decreased for two subjects. similarly, there was no change in trail MFC for the majority of subjects (83%). Of the five subjects (17%) with slopes that were significantly different from zero: MFC increased for two subjects and decreased for three subjects. since there was no consistent change in lead or trail MFC for the majority of subjects, the average of all 25 trials from epoch 2 was used for the remaining analyses. Therefore, there was no evidence of memory decay in the MFC of either lead or trail limb in epoch 2.

5.5.1.7 Adaptation Effects for Real Obstacle; Epoch 1 Versus 3

Epoch 1 was not different from epoch 3 for all measures, demonstrating that subjects did not adapt their behavior as a function of repeated observations with the real obstacle (Figure 11, Figure 12). Therefore, any differences between epoch 2 and epoch 1 are due to the virtual obstacle manipulation.

5.5.1.8 Real Versus Virtual Obstacle; Epoch 1 Versus 2

Post hoc analyses revealed that the following measures all decreased for the virtual obstacle ($p \leq 0.001$ for all measures): lead and trail MFC (Figure 11a, b), trail toe peak (Figure 11d), and lead toe peak position (Figure 12a). The following variability measures increased for both the lead and trail limbs ($p \leq 0.001$): MFC variability (Figure 11e, f), toe peak variability (Figure 11g, h), and toe peak position variability (Figure 12c, d). There were no differences in horizontal distance or stride length.

5.5.2 Experiment 2

5.5.2.1 Contacts with the Real Obstacle

Six contacts with the real obstacle were observed in six subjects, for a contact rate of 0.5%; all contacts were with the trail limb. These six subjects were excluded from further analyses, resulting in 18 subjects. Toe peak was examined to determine whether subjects elevated the foot the same amount for real and virtual obstacles. Similar to Experiment 1 (Figure 11c), lead toe peak was not different for real versus virtual obstacles for both the 15- and 25-cm obstacles. Trail toe peak was not different for real versus virtual obstacles for the 15-cm obstacle, but was lower for the 25-cm virtual obstacle compared to the large real obstacle ($p < 0.001$), consistent with Experiment 1 (Figure 11d). Next, toe peak of the virtual trajectories was compared for 15- versus 25-cm obstacles, to determine whether the limb elevation when guided by memory was scaled to the obstacle height. toe peak was significantly higher for the 25-cm versus 15-cm virtual obstacle for the lead foot (38.7 ± 3.2 vs 30.2 ± 3.1 cm, $p < 0.001$) and the trail foot (40.7 ± 5.5 vs 32.3 ± 4.9 cm, $p < 0.001$). These changes confirmed that subjects were scaling the trajectory to the height of the virtual obstacle.

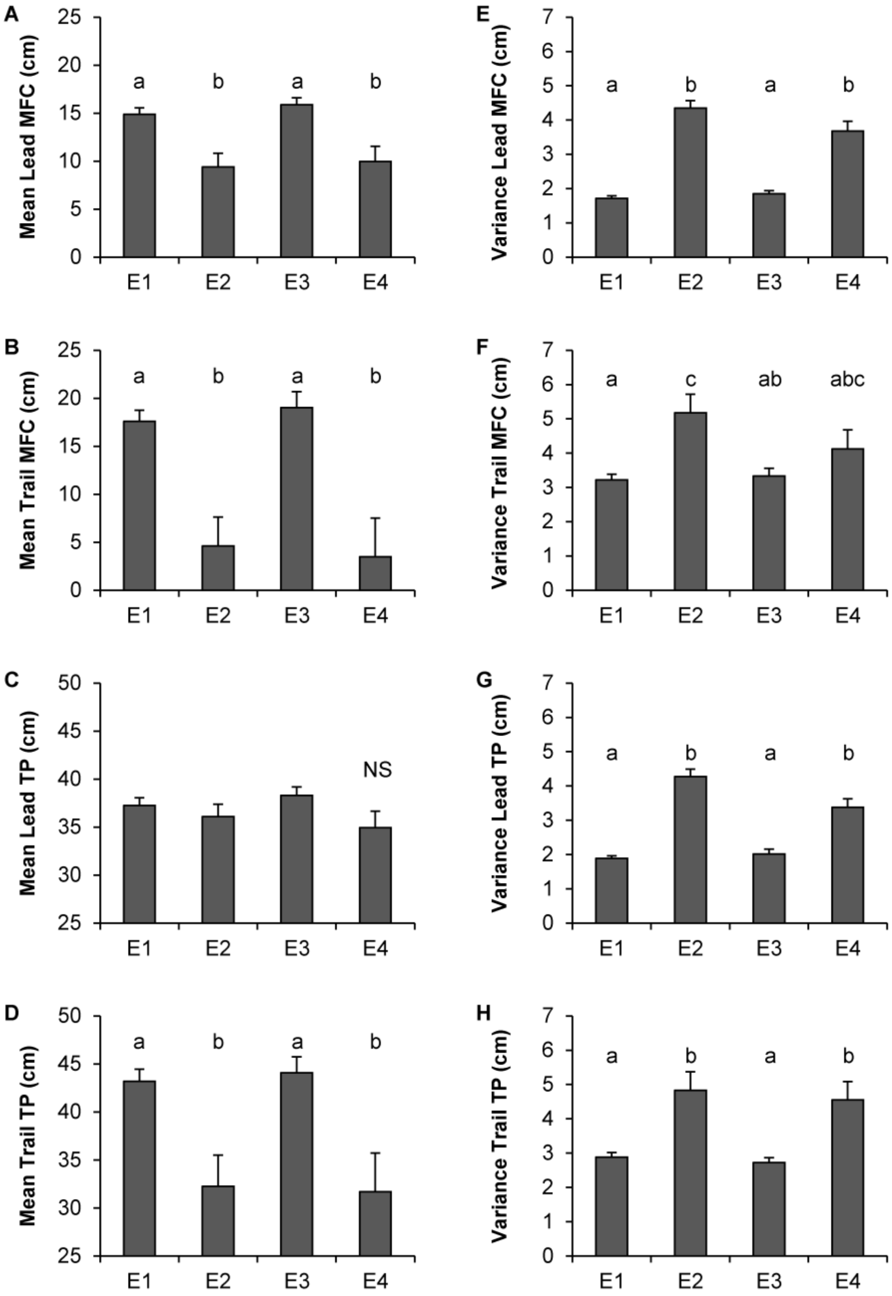

Figure 11 Mean (left panel) and variability (right panel) of dependent variables during epochs 1–4 (E1, E2, E3, and E4). E1 and E3 have a real obstacle, E2 and E4 have a virtual obstacle. Lead minimum foot clearance (a), trail minimum foot clearance (b), lead toe peak elevation (c), trail toe peak elevation (d), variability of lead minimum foot clearance (e), variability of trail minimum foot clearance (f), variability of lead toe peak elevation (g), and variability of trail toe peak elevation (h). Error bars indicate standard error. Different letters indicate significant differences ($p < 0.01$). NS indicates no significant effect of epoch.

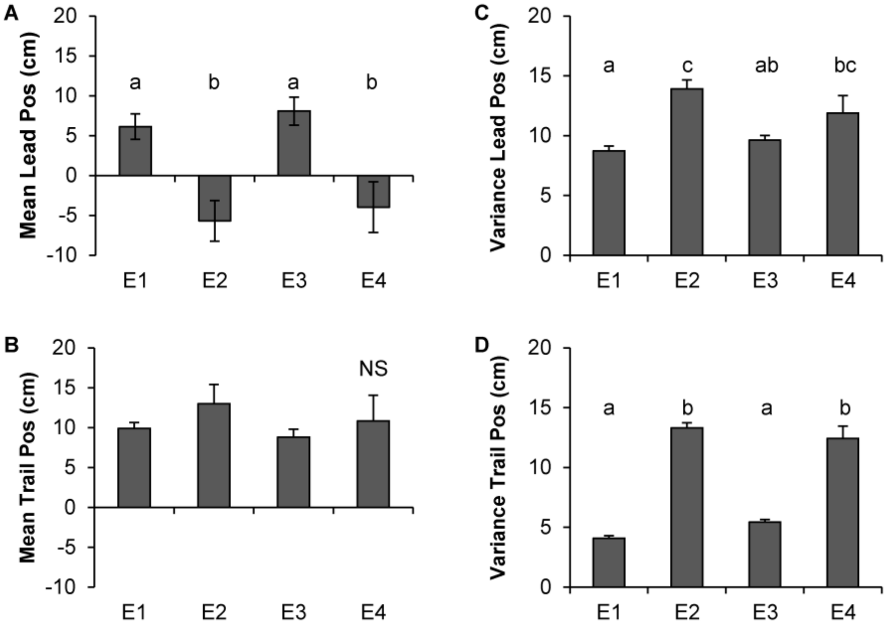

Figure 12 Mean (left panel) and variability (right panel) of dependent variables during epoch 1–4 (E1, E2, E3, and E4). E1 and E3 have a real obstacle, E2 and E4 have a virtual obstacle. Lead toe peak position (a), trail toe peak position (b), variability of lead toe peak position (c), and variability of trail toe peak position (d). Error bars indicate standard error. Different letters indicate significant differences ($p < 0.01$). NS indicates no significant effect of epoch.

5.6 Discussion

The aim of this paper was to determine whether an obstacle memory could guide action. The obstacle was not present and thus did not provide online visual guidance. However, unlike previous research (Mohagheghi et al., 2004; Patla & Greig, 2006), vision of the environment was preserved, including a visible obstacle position cue, so that we specifically examined whether obstacle height memory could accurately guide action. No changes in foot placement were observed; therefore, the position cue provided salient online information to guide foot placement. However, the failure rates of 9 and 47% for the lead and trail limb, respectively, indicate that the ability to successfully clear the virtual obstacle was compromised when relying on an obstacle memory. The higher variability of the trajectory characteristics demonstrate reduced precision when relying on an obstacle memory. In order to accept the preceding interpretations, it is important to demonstrate that subjects were genuinely attempting to clear the obstacle and that an obstacle memory was formed. Genuine attempts to clear the obstacle are confirmed by the observation that lead toe peak height was not different for real and virtual obstacles (Figure 11c) and the clear attempts of subjects 2 and 19 to clear the obstacle (Figure 8). The observation that both lead and trail toe peaks were scaled to the height of the virtual obstacle in Experiment 2 confirms that an obstacle memory had been formed. Therefore, it appears that participants were using an obstacle memory to guide action, but the action was compromised, perhaps due to an imprecise obstacle memory. We first describe why subjects failed with the lead limb, why they failed more frequently with the trail limb, and then consider why action was not successfully guided by an obstacle height memory, given the empirical support for long-lasting obstacle memories (Lajoie et al., 2012; McVea & Pearson, 2006, 2007; Shinya et al., 2012; Whishaw et al., 2009).

The lead limb trajectories were qualitatively similar for real and virtual obstacles (Figure 8, Figure 9), although differences in the kinematics appear to reflect a position misjudgment and reduced precision. While toe peak was not different, the position of the toe peak within the stride was shifted backwards (Figure 12a), and the clearance was reduced for the virtual obstacle (Figure 11a), due to a steeper descent after the peak (Figure 8, subjects 8, 13, and 19). These changes may reflect a position misjudgment where the subject perceived that the virtual obstacle was closer to the stance foot. An obstacle position misjudgment was unexpected because the position of the lower edge was provided with a high contrast length of masking tape and there was no difference in foot placement. If information regarding obstacle height and position of the lower edge is available, it is reasonable to expect that the position of the top edge is also available. However, the 9% failure, the decrease in clearance, and the shifted location of the toe peak are not consistent with this expectation. It should be pointed out that while the average lead limb failure rate was 9, 63% of subjects did achieve 5% failure or less. However, the higher variability of clearance, toe peak, and toe peak position (Figure 11e, g, Figure 12c) for the virtual obstacle demonstrate reduced precision. Further, the average clearance of the failed trials was 1.7 cm, which is moderately high (about 8% of the obstacle height). Overall, these findings indicate that an obstacle height memory provided some success with the lead limb, although not as high as predicted, but the action was compromised.

The trail limb failure rate (47%) was almost ten times greater than the predicted failure rate of 5% (Table 3). What is most striking during trail limb crossing of a virtual obstacle is the wide variety of behavior apparent in the trajectories (Figure 8, Figure 9). Subject 2 moved the foot backwards up to 25 cm after toe-off and elevated the toe up to 70 cm for a 19.5-cm obstacle. The peaks of subjects 8 and 13 only reach about half the height of the obstacle. Subject 19 increased toe clearance 250%, and subject 32 adopted a trail limb trajectory with a triangular shape that was more similar to lead limb trajectories. the high trail limb failure rate, coupled with the qualitative changes in the trajectories (Figure 8) and the large quantitative changes in the means and variability of the trajectory characteristics (Figure 11, Figure 12), clearly demonstrates that relying on an obstacle height memory compromised the control of the trail limb trajectory.

These failures and high trajectory variability are strikingly different from the successes observed in the previous literature (Lajoie et al., 2012; McVea & Pearson, 2006, 2007; Whishaw et al., 2009). The main difference with the preceding studies is that the obstacle was visible during approach and/or lead limb crossing. Therefore, for both the lead and trail limb, it appears that the obstacle must be viewed during approach to form a memory that can successfully guide the action. It was not adequate to view the position (masking tape) and combine that information with obstacle height memory. Memories formed during approach and memories formed from previous experience may reside in separate systems for spatial representation (Milner et al., 2003; Milner & Goodale, 1995); these separate systems would explain the differences between this study and previous obstacle crossing research. The dorsal system is responsible for the immediate guidance of action, while the ventral system is involved in delayed guidance of action. Previous research, where the obstacle was viewed during approach, would likely involve memory related to the dorsal visual stream. the dorsal visual stream projects to the parietal cortex, and neurons in the parietal cortex are active transiently when an animal steps over an obstacle (Drew, Andujar, Lajoie, & Yakovenko, 2008) and remain active when an animal straddles the obstacle (Lajoie, Andujar, Pearson, & Drew, 2010). The current paradigm would have relied on visual information that lasts longer than the transient information available within the dorsal stream. The more persistent – and less precise – visual information of the ventral stream would be used (Milner et al., 2003), leading to a high failure rate and reduced precision in trajectory control. This interpretation is similar to that of Shinya et al. (2012): climbing stairs after vision was diverted for a few seconds appears to involve the less precise ventral system.

There is little evidence that the obstacle memory degraded during the course of epoch 2 (about 9 min), which likely reflects that participants were already relying on the less precise ventral system from the first trial in epoch 2. the only support for memory decay was the increase in trail failure (Figure 10), but the increase was driven by only four subjects (13%). the lack of decay was likely due to the relatively long interval, approximately 30 s, between crossing the last real obstacle in epoch 1 and the first virtual obstacle in epoch 2. In a similar approach with stair climbing, maximum toe clearance increased most within a 2-s period between diverting vision from the stair and step initiation. Therefore, the paradigm adopted here did not allow for evidence of decay. The lack of change reflects that the less precise obstacle memory, presumably from the ventral system, was relatively stable over the 9-min interval.

The high failure rates in the virtual obstacle condition support Gibson’s argument that dynamic visual sampling, achieved during the approach to the obstacle, is beneficial for the guidance of action (Gibson, 1958, 1966). The obstacle memory would likely be a static representation and would likely be devoid of the rich information gained by viewing the obstacle while moving through the environment. These observations also build on previous research that demonstrated that vision of the interface of the obstacle and walkway (the lower edge) is important for successful crossing (Rietdyk & Rhea, 2011). Therefore, it appears that the full obstacle must be visible, top and lower edge, at least three steps before crossing the obstacle in order to successfully guide the limb trajectory.

If the lead limb trajectory was used to calibrate or control the trail limb, one would expect that the failure rates would be similar for the two limbs, but substantially different failure rates were observed (Table 3; Figure 8, Figure 10). These differences add to the converging evidence that the limbs are controlled independently during obstacle crossing in humans (Niang & McFadyen, 2004; Patla et al., 1996; Rhea & Rietdyk, 2011; Yang et al., 2004). The observation that an obstacle memory was more successful at guiding the lead than the trail limb can be interpreted two ways. First, the instructions in epoch 2 reminded the subject to cross the obstacle with the right (lead) limb first, but did not specifically refer to the trail limb. In dual-task paradigms, subjects perform better in the task that they are instructed to attend to (Kelly, Janke, & Shumway-Cook, 2010; Siu & Woollacott, 2007; Yogev-Seligmann et al., 2010). Since the original instruction referred to the lead limb, but not the trail limb, the instruction may have resulted in the subject paying more attention to the lead limb. When instruction referred to both lead and trail limb in epoch 4, failure rate decreased significantly for both limbs (Table 3; Figure 9). Therefore, subjects apparently perceived that both lead and trail trajectories were not adequate and compensated with both limbs. However, the trail limb failure rate was still higher. Therefore, the observations do not support instruction as a plausible explanation for the high trail limb failure rate. The second explanation is that information of limb position relative to the obstacle (termed exproprioception) was compromised more for the trail limb than the lead limb. The trail limb action is guided by obstacle memory combined with kinesthetic information regarding current limb position and motion. The lead limb action is also guided by memory combined with kinesthetic information, but online visual information (the thigh is visible in the lower periphery) is also available and is likely used to update and calibrate the movement during the swing phase (Patla, 1998; Rietdyk & Rhea, 2006). Therefore, viewing the obstacle during approach is more critical for successful trail limb crossing than lead limb crossing.

More frequent trail contacts, observed here with virtual obstacles, are also observed with real obstacles. Therefore, the current findings may provide insight into the causes of trail limb failures with real obstacles. Trips can occur due to unexpected changes in surface height, but they also occur when an individual perceived an obstacle, but failed to elevate the limb adequately. In the lab setting, when young, healthy adults contact a visible, stationary obstacle under the conditions of normal lighting and full vision, the contact rate is about 1–2% (Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), and the trail foot is the contact foot 67–100% of the time (Berard & Vallis, 2006; Heijnen et al., 2012a; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007, 2011; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011). Note that the contacts with the real obstacles in the current paradigm have a similar rate (0.5%) and were also mostly trail limb contacts (90 & 100%). One potential mechanism behind these trail limb contacts with a real obstacle is that visual fixations during approach were absent or inadequate. There is a fair amount of inter and intrasubject variability in obstacle fixations during approach to an obstacle, and in up to 33% of the trials, subjects did not fixate on the obstacle at all (Patla & Vickers, 1997).

This would result in insufficient visual information to successfully guide the action with the dorsal system, and the individual would presumably be forced to rely on the less precise ventral system. Lack of adequate visual information should compromise both lead and trail limb trajectories, but the lead limb trajectory can be updated by online visual information while the trail limb cannot, ultimately resulting in higher trail limb contact rates.

The virtual obstacle trail limb trajectories reported here for young healthy subjects have similarities with real obstacle trajectories described in balance-compromised subjects in two studies. First, subject 2 (Figure 8) and another subject (not shown) demonstrated backwards displacement of the trail limb after toe-off for the virtual obstacle. A similar backward horizontal overcorrection has been observed in older women when taking a single step over an obstacle, and this was interpreted as a larger clearance margin to maintain safety (Berg & Blasi, 2000). Extrapolating the interpretations described here for young adults with virtual obstacles to older adults with real obstacles, it is also possible that the backwards foot displacement of older women may be related to compromised ability to gather, store, and/or use obstacle information in the single step task. second, subject 32 (Figure 8) and another subject (not shown) had triangular shaped trail limb trajectories for the trail obstacle; the shape is similar to the trail limb trajectory of a 4-year-old girl with early bilateral lesion of the occipital cortex (Amicuzi et al., 2006). It was concluded that the lesion eliminated the detection of visual information that specified how to interact with the obstacle. This conclusion could be extended to the current findings that vision of the obstacle during approach specifies how to interact with the obstacle; while an obstacle memory may provide height information, it is not adequate for guiding the trail limb trajectory.

In summary, when an obstacle memory was not formed during the current approach, the control of the trajectory was impaired, ultimately resulting in a high failure rate. The failure rate was four times higher for the trail limb than the lead limb. Since the lead limb is visible in the lower periphery during crossing, vision of the limb, combined with stored height information, can be used to guide the lead limb more successfully than the trail limb. However, 9% lead limb failure is relatively high, given that lead limb failures in young, healthy adults are rarely observed (Berard & Vallis, 2006; Heijnen et al., 2012a; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006). Action was impaired to a greater extent for the trail limb, which is likely due to the fact that the trail limb is not visible during crossing. These results emphasize that the dynamic visual input gained during approach is critical for success.

CHAPTER 6. INTERMISSION II: WHAT WE HAVE LEARNED SO FAR

Study 2 in the previous chapter examined failures when participants were forced to rely on an obstacle memory from previous interactions with the obstacle. Several factors were established. First, it was demonstrated that an obstacle memory was used to guide both the lead and trail limb, as both limbs scaled their trajectories accordingly to different obstacle heights. Second, failure rates were 9 and 47% for the lead and trail limb, respectively when only an obstacle memory was available to guide the limb trajectories. These failure rates are substantially larger than the 1% failure rate observed in the first study (Chapter 3). Third, more failures occurred with the trail limb, similar to the first study (Chapter 3). Fourth, the majority of failures occurred due to inadequate foot elevation. A position cue provided online visual information regarding obstacle position, which meant that participants were able to correctly place their foot. Finally, these findings reiterate the importance of feedforward visual information obtained during the approach. Note that in this study, feedforward information was obtained from previous trials, not the current trials.

The previous chapters have examined two extremes: Study 1 (Chapter 3) examined obstacle crossing when all sensory sources were available while Study 2 (Chapter 5) examined obstacle crossing when visual feedforward information and somatosensory information regarding obstacle contact were not available. The next study (Chapter 7) will examine obstacle crossing behavior when sensory sources are partially available. Specifically, the visual information will not be manipulated, while somatosensory information regarding obstacle contact will be removed. Compared to study 1 (Chapter 3) participants will have the same information available during the approach phase and crossing phase of the lead limb, but knowledge of results (provided by somatosensory information regarding obstacle contact) will be removed for the trail limb. Recall that in Study 1, the majority of participants demonstrated a progressive decrease in foot elevation until contact occurred, and in Study 2, participants were relying on stored information, an obstacle memory, to complete the task. The progressive decrease in foot elevation observed in Study 1 is consistent with a progressive decrease of the obstacle height in the obstacle memory. Following obstacle contact in Study 1, foot elevation increased 75%, indicating that knowledge of results updated the obstacle memory. Removing this knowledge of results will determine if the memory continues to drift, indicating that physical contact is necessary to update the feedforward visual information regarding the obstacle height.

CHAPTER 7. FAILURES IN ADAPTIVE LOCOMOTION: WIDE VARIETY IN BEHAVIOR AS A FUNCTION OF REPEATED TRIALS

7.1 Specific Aim

To determine the contribution of somatosensory information to accurately guide the lower limb trajectory over an obstacle in healthy young adults; in particular, to determine if physical contact is necessary to update the obstacle height memory.

7.2 Abstract

Knowledge of obstacle characteristics, termed obstacle memory, must be available for the trail limb to successfully cross the obstacle. Heijnen et al. (2012a) showed an apparent drift in the trail foot clearance of 1 mm per trial. This drift in performance may reflect a drift in obstacle memory. When foot clearance reached zero, somatosensory information from obstacle contact provided knowledge of results, which was used to update the obstacle memory as indicated by the large increase in foot clearance following obstacle contact. In the present study, this knowledge of results was removed to determine if an obstacle memory could accurately guide the trail limb over an obstacle. Participants crossed an obstacle with the lead limb, but directly following lead limb crossing, the obstacle dropped down which removed the knowledge of results, so that the memory was not updated if the foot was too low. It was predicted that foot clearance would either decrease linearly below the actual obstacle height or demonstrate an asymptotic curve

that gradually approached the obstacle height. Unexpectedly, both behaviors were observed: 52% demonstrated an asymptotic curve and 24% demonstrated a linear decrease. In the former, the obstacle memory became more accurate with repeated trials; in the latter, it appears to become less accurate with repeated trials. This interpretation is consistent with the observation that the linear group had a greater percentage of virtual failures (contacts that would have occurred if the obstacle had not dropped down) than the asymptotic group (19 vs 8%, p=0.01). The variety in behavior could be related to gaze behavior, as visual information regarding obstacle characteristics may be gathered differently between these two groups and highlights the difficulties in the development of universal fall-prevention programs. The average failure rate of 8% was greater than the 1-2% observed for stationary, visible obstacles, which indicates that knowledge of obstacle contact is instrumental in guiding the limb trajectory.

7.3 Introduction

Vision allows an individual to sample the environment from a distance in order to proactively plan to avoid an obstacle or other potential hazards. Visual information regarding an obstacle is sampled in two ways, including feedforward (i.e. sampled at a distance before obstacle crossing) and online (i.e. sampled during the swing phase trajectory as the foot crosses the obstacle). Although vision is critical for successful obstacle negotiation (Heijnen et al., 2014; Mohagheghi et al., 2004; Patla, 1998; Patla & Greig, 2006; Patla & Rietdyk, 1993; Patla et al., 1996), it is not the only source of sensory information that is available; somatosensory information provides information such as joint angles and touch. Examining the roles of visual and somatosensory information in adaptive locomotion is important to determine why people fail to clear a visible, stationary obstacle and will increase the understanding of the contribution of these sources of sensory information to guiding the limbs successfully over the obstacle.

Information available to guide the lead limb (first limb to cross the obstacle) includes feedforward visual information gathered during approach phase, online visual information, and somatosensory information (Table 1). Vision provides information about the obstacle characteristics, and the position of the person relative to the obstacle. Somatosensory provides information about the limb movement and position, including contact with the environment. Information available to guide the trail limb (second limb to cross the obstacle) is limited to feedforward visual information and somatosensory information (Table 1). The critical difference between the two limbs is that the lead limb is visible in the lower visual field and can use online visual information to fine-tune the limb trajectory while the trail limb cannot. The lack of online visual information for the trail limb is believed to result in more frequent failures with the trail limb than the lead limb (Patla et al., 1996; Rietdyk & Rhea, 2006; Rietdyk & Rhea, 2011).

For the trail limb to successfully cross the obstacle, knowledge of obstacle characteristics must be available. This obstacle knowledge is created from information gathered during the approach and/or from previous interactions with the same or similar obstacles. The information can be provided from multiple sources, including visual, somatosensory, and/or efference copy. This obstacle knowledge has been termed a “stored obstacle representation” (Lajoie et al., 2012) or an “obstacle memory” (McVea & Pearson, 2006, 2007; Shinya et al., 2012; Whishaw et al., 2009); the term “obstacle memory” to refer to the knowledge of obstacle characteristics. Multiple studies have demonstrated that an obstacle memory can be used to accurately guide lower limb trajectories over an obstacle (Heijnen et al., 2014; Lajoie et al., 2012; McVea & Pearson, 2006; Shinya et al., 2012; Whishaw et al., 2009).

As stated above, the information available to guide the trail limb is limited to feedforward visual information and somatosensory information. Heijnen et al. (2012a) showed an apparent drift in the foot clearance measure with repeated trials, where the clearance progressively decreased by about 1 mm per trial. It is possible the first trials were completed with extra high clearance to ensure no contact, with a gradual improvement in performance in successive trials. However, the progressive decrease continued until the trail foot contacted the obstacle for the majority of the participants (70%), demonstrating a decrease in performance with successive trials. This drift is unexpected since the prevailing argument for adaptive gait is that safety is paramount (Patla, 1991). While this behavior was unexpected, a similar drift has also been observed in upper limb tasks (Ambike et al., 2015; Vaillancourt & Russell, 2002), and it has been argued that the drift in performance reflects a drift in the memory (Vaillancourt & Russell, 2002). In the locomotor task, the drift results in the foot clearance reaching zero, and somatosensory information from the obstacle contact provides knowledge of results, which can be used to update the obstacle memory. The large increase in foot clearance after contact (Heijnen et al., 2012a; Rhea & Rietdyk, 2011) is consistent with an updating of the obstacle memory following knowledge of results. In the present study, this knowledge of results was removed.

Participants crossed an obstacle with the lead limb, but directly following lead limb crossing, the obstacle dropped down. Unlike previous studies (Lajoie et al., 2012; McVea & Pearson, 2006; Whishaw et al., 2009), the participants did not pause while straddling the obstacle, they walked smoothly and continuously, and they were not aware that the obstacle had lowered for the trail limb crossing. Two different types of behavior were possible for those participants who demonstrate a decrease in foot clearance with repeated trials: 1) a linear decrease in trail foot clearance, resulting in values that would result in contact if the obstacle was still in place (Figure 13A), or 2) a decrease in trail foot clearance along an asymptotic curve which approaches the obstacle height (Figure 13B). If a linear decrease is observed, then it will be apparent that the obstacle height

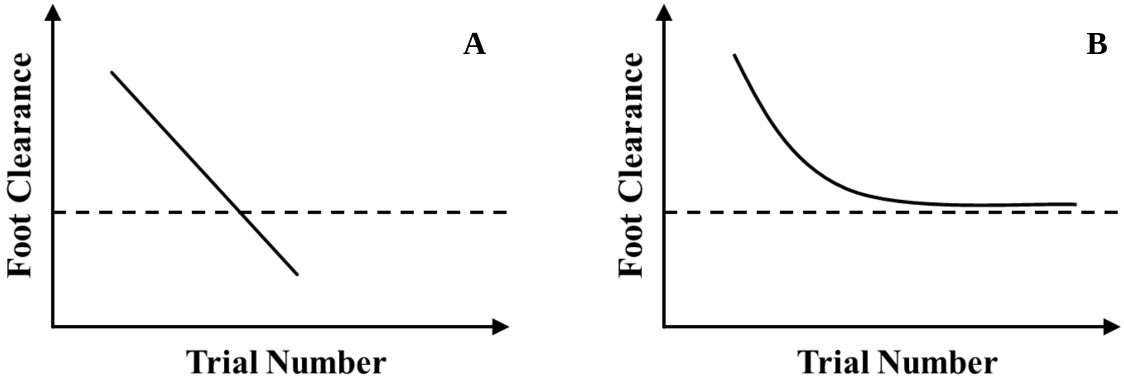

Figure 13 Two different types of behavior are possible: the trail foot clearance either continues to progressively decrease to levels that would result in contact if the obstacle was still in place (A), or the trail foot clearance will level off at the height of the obstacle (B). Dashed horizontal lines represent foot clearance of zero, or where the foot would contact the obstacle if it were still in place.

memory drifts over time, and the cause of the contact is an inaccurate memory (Figure 13A). However, if an exponential decrease is observed, and the flat region is at or above the obstacle height, then feedforward visual information is accurately guiding the trail limb and the obstacle memory is apparently becoming more accurate with each successive trial (Figure 13B). The cause of any contacts in this case would be clearance variability that is high enough to result in occasional errors.

7.4 Methods

Twenty-seven healthy young adults participated in this study (19.9 ± 0.9 years; 10 males). Participants were free from any impediments to normal locomotion, and had normal or corrected-to-normal vision, as verified by self-report. All participants signed a consent form approved by the local Institutional Review Board.

Participants walked at a self-selected pace on a 12-m walkway and stepped over an obstacle in the middle of the walkway for 150 trials. Position data of infrared emitting diodes (IREDs) were recorded with a Phoenix motion capture system (Visualeyez^{TM}, Phoenix Technology Inc., Burnaby, BC, Canada) at 60 Hz. IREDs were placed on the lateral aspect of the left foot at the distal phalanx of the third toe, calcaneus, and malleolus and on the medial aspect of the right foot at the distal phalanx of the first toe and calcaneus. Two IREDs were placed on the left temporal region of the head, and one IRED was placed on the top of the obstacle.

In each trial, the participant walked down the walkway, stepped over an obstacle, continued to the end of the walkway, completed a short computer task at the end of the walkway, and returned to the start of the walkway. The obstacle was custom made and designed to drop down without the participant's knowledge after the lead limb crossed the obstacle (Figure 14). A laser beam was projected horizontally across the walkway and was used to trigger the obstacle drop. A receiver measured the light intensity from the laser beam in arbitrary units (0-1000). If the value dropped below 300 (i.e. when the lead limb broke the laser beam), two solenoids were activated to release the obstacle, and the top edge of the obstacle dropped 7.5 cm in 150 ms. The obstacle was 20 cm high, 100 cm wide, and 1 cm deep and designed to tip when contacted (similar to a hurdle). Obstacle height reduced from 20 to 12.5 cm for the trail limb crossing on each trial. There were several factors to reduce the likelihood that participants were aware that the obstacle dropped down. First, to ensure the obstacle was completely out of view in the lower visual field before it dropped down, the laser was mounted on a rod, located 42 cm above the ground, and 30 cm after the obstacle (Figure 14). Second, to create the illusion of a solid obstacle, the obstacle was covered in black fabric. Third, to prevent participants from hearing the obstacle drop, the top part of the obstacle dropped to a padded base, and noise cancelling headphones (QuietComfort 15, Bose, Framingham, MA) were worn playing white noise. Finally, to allow the experimenter enough time to raise the obstacle to the original height after each obstacle crossing, a reaction time task was set up at the end of the walkway; participants completed this computer task in approximately 10 seconds, then returned to the start of the walkway.

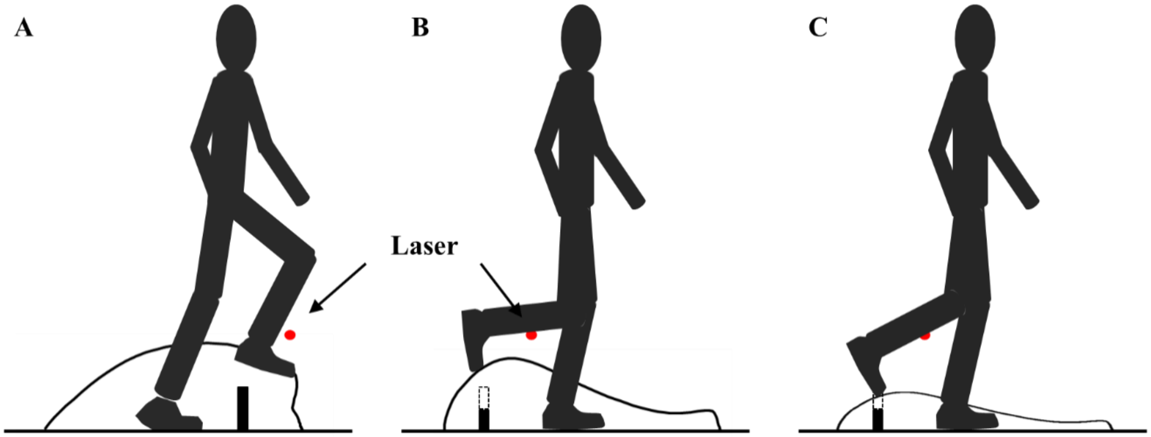

Figure 14 Experimental setup. The obstacle was visible and stationary during the approach and crossing phase of the lead limb. During approach, the participant always observed a 20 cm obstacle. After the lead limb broke the laser beam (projected horizontally across the walkway) (A), the obstacle dropped down without the participant’s knowledge (B). Obstacle height reduced from 20 to 12.5 cm for the trail limb crossing; this occurred in every trial. The lower height allowed the trail limb trajectory to go through the dropped down portion of the obstacle without any somatosensory feedback from obstacle contact (C). Thus, if the trail limb was not adequately elevated, the participant received no feedback, as they would have if the obstacle had not dropped down.

Data was analyzed with MATLAB 2013a software (MathWorks Inc., MA, USA) and filtered offline at 8 Hz with a fourth-order zero-phase-shift low-pass Butterworth digital filter (Winter, 2009). Foot clearance, foot placement, and gait speed were calculated. Foot clearance was calculated for the toe and the heel as the vertical distance between the toe/heel IRED and the IRED on the obstacle. The minimum between toe and heel clearance was used for foot clearance, as the toe is not always closest to the obstacle for the lead limb. Using toe clearance alone can lead to an overestimation of foot clearance (Heijnen et al., 2012a; Loverro et al., 2013; Thies et al., 2011). To reduce errors in the foot clearance measure due to high foot velocities, toe and heel trajectories were interpolated with a cubic interpolation (Heijnen et al., 2012b). Foot placement was calculated as the horizontal distance between the toe IRED and the obstacle IRED. Foot clearance and foot placement were calculated for both the lead and trail limb. Gait speed was calculated as the anterior-posterior velocity of the shoulder from lead toe-off before the obstacle until trail toe-off after the obstacle, which includes both the lead and the trail foot crossing the obstacle.

Failure rates were calculated as the percentage of obstacle contacts if the obstacle had not been lowered. These contacts are termed “virtual contacts”, and are only available for the trail limb, since only the trail limb stepped over the 20 cm virtual obstacle.

Foot clearance was examined as a function of trial number. To quantify the adaptation, a linear regression and an exponential regression were calculated in MATLAB for each participant. A custom equation was used to calculate the exponential regression: $y = a * e^{\left(-\frac{x}{\tau}\right)} + b$, where y is the foot clearance, x is the trial number, and a, b, and τ are parameters calculated by MATLAB. A paired t-test ($p < 0.05$) was used to compare the adjusted coefficient of determination (adjusted R^2) of a linear regression to the adjusted coefficient of determination of an exponential regression. Obstacle contacts alter obstacle crossing behavior on the subsequent trials (Heijnen et al., 2012a; Rhea & Rietdyk, 2011); therefore, if a participant contacted the obstacle, the regression was calculated until the trial before obstacle contact.

Participants were classified into three groups based on their adjusted R^2 values (Figure 15). First, to determine if a relationship existed between foot clearances and the number of trials, the threshold was set to adjusted $R^2 \geq 0.25$ for either the linear or the exponential fit. A value of 0.25 was selected as this corresponds to a moderate relationship in Pearson's correlation ($r = 0.5$). Participant with an adjusted $R^2 \geq 0.25$ participants were then classified as having either a linear or an asymptotic relationship. Participants with an exponential adjusted R^2 of 0.05 or greater than the adjusted R^2 of a linear fit were classified as asymptotic; adjusted R^2 values that did not meet this criteria were classified as having a linear relationship. Participants with an adjusted $R^2 < 0.25$ were classified as having no relationship between foot clearance values and trial number. For the participants who were classified as having a linear decrease, the slope of the linear regression was calculated for the lead and trail limb.

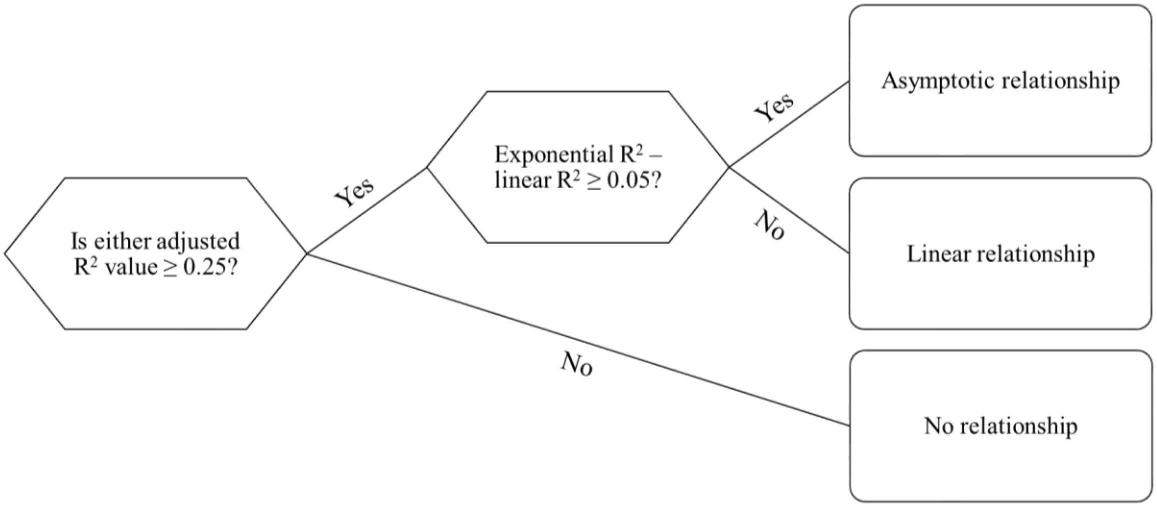

Figure 15 Decision tree to classify participants into one of three groups: asymptotic relationship, linear relationship, or no relationship.

In addition, two researchers qualitatively examined the foot clearance as a function of repeated trials to confirm the quantitative analysis. Foot clearance behavior was categorized as 1) linear decrease in foot clearance, or 2) an asymptotic curve with foot clearance approaching the obstacle height (i.e. an initial linear decrease in foot elevation, but this decrease ultimately reduced with the flat region value similar to the height of the obstacle). Cohen’s κ was calculated in SAS 9.3 (Cary, NC, USA) to assess the inter-rater reliability between the two researchers.

7.5 Results

Six participants were excluded from further analyses. Four participants were excluded due to technical issues related to the obstacle; the obstacle either failed to drop down fully or dropped down prematurely as the participant approached the obstacle. One participant was excluded due to data collection equipment issues. One participant was excluded due to an early contact (trial 13). The following results include the remaining 21 participants.

7.5.1 Physical Contacts with the Obstacle

Fourteen participants never contacted the physical obstacle (67% of all participants). Seven participants physically contacted the obstacle for a total of nine contacts out of 3146 trials, or 0.3%. Two contacts occurred with the lead limb (22%), seven contacts were with the trail limb (78%). All lead limb contacts occurred with the 20 cm obstacle, all trail limb contacts occurred with the lowered, 12.5 cm obstacle, indicating that they misjudged the height of the obstacle by at least 7.5 cm or 38% of the total height.

7.5.2 Contacts with the Virtual Obstacle

Thirteen participants (62%) would have contacted the 20 cm obstacle with the trail limb at least once if it had not dropped down; these were termed virtual contacts. Virtual trail limb contacts are observed in Figure 16, participants 2, 13 and 23, right panel: several clearance values are in the gray region, indicating the participants would have hit the obstacle on those trials if the obstacle had not been lowered. A total of 266 virtual contacts were made out of 3146 trials, or 8%. Individual failure rates with the virtual obstacle ranged from 0 to 39%. Participants were classified into two categories based on the percentage of trials with a virtual contact.

7.5.3 Comparisons of Adaptation Effect for the Trail Limb

Adjusted R^2 values for the exponential regression were statistically greater than the linear regression (0.46 vs 0.41 for exponential and linear regression, respectively; $p = 0.01$). However, this analysis does not take the wide range of behavior of participants into account. For example, participant 20 had very low values for both linear and exponential fits (Table 4), visual examination of this data indicated that the participant had similar behavior to others up to trial 40, but then the behavior changed, which caused the low adjusted R^2 value (Table 4). Two participants demonstrated similar behavior, so additional regressions were calculated until the observed change in behavior (Table 4), with the transition determined subjectively by the experimenters. Following this cutoff, adjusted R^2 values for the exponential regression remained statistically greater than the linear regression (0.51 vs 0.44 for exponential and linear regression, respectively; $p = 0.004$).

Examination of individual R^2 values indicated that, while the majority of subjects demonstrated this behavior, ten participants did not follow this trend. Adjusted R^2 values of these participants were similar for linear and exponential regression. Of these ten participants, three demonstrated adjusted R^2 values close to zero (participants 5, 8, and 22; Table 4). Visual examination of these participants indicated that they did not change foot clearance over time as the average slope of the linear regression was 0.0 mm/trial.

Overall, examination of trail limb foot clearance indicated that eleven participants (52%) started with a progressive decrease in foot elevation, but this decrease ultimately reduced with the flat region value similar to, or slightly above, the height of the obstacle (e.g. participant 2 and 23 in Figure 16). Seven participants (33%) showed a linear decrease in foot clearance (e.g. participant 13 and 14 in Figure 16). The remaining three participants (14%) did not change trail foot clearance as a function of trial number. Cohen's $\kappa = 0.80$ (95% CI 0.58-1.00), indicating a substantial agreement between the two researchers (Viera & Garrett, 2005). The average slope of the linear regression for the participants who were classified as having a linear decrease in foot clearance was -1.1 mm/trial.

7.5.4 Comparisons of Adaptation Effect for the Lead Limb

To quantify the adaptation effect in lead foot clearance as a function of trial number, coefficients of determination (adjusted R^2 values) were compared between a linear and exponential regression. No statistical difference was observed between the adjusted R^2 values (0.20 vs 0.22 for exponential and linear regression, respectively; $p = 0.47$; Table 5).

For the participants who were classified as having a linear decrease in trail foot clearance, the slope was -0.3 mm/trial.

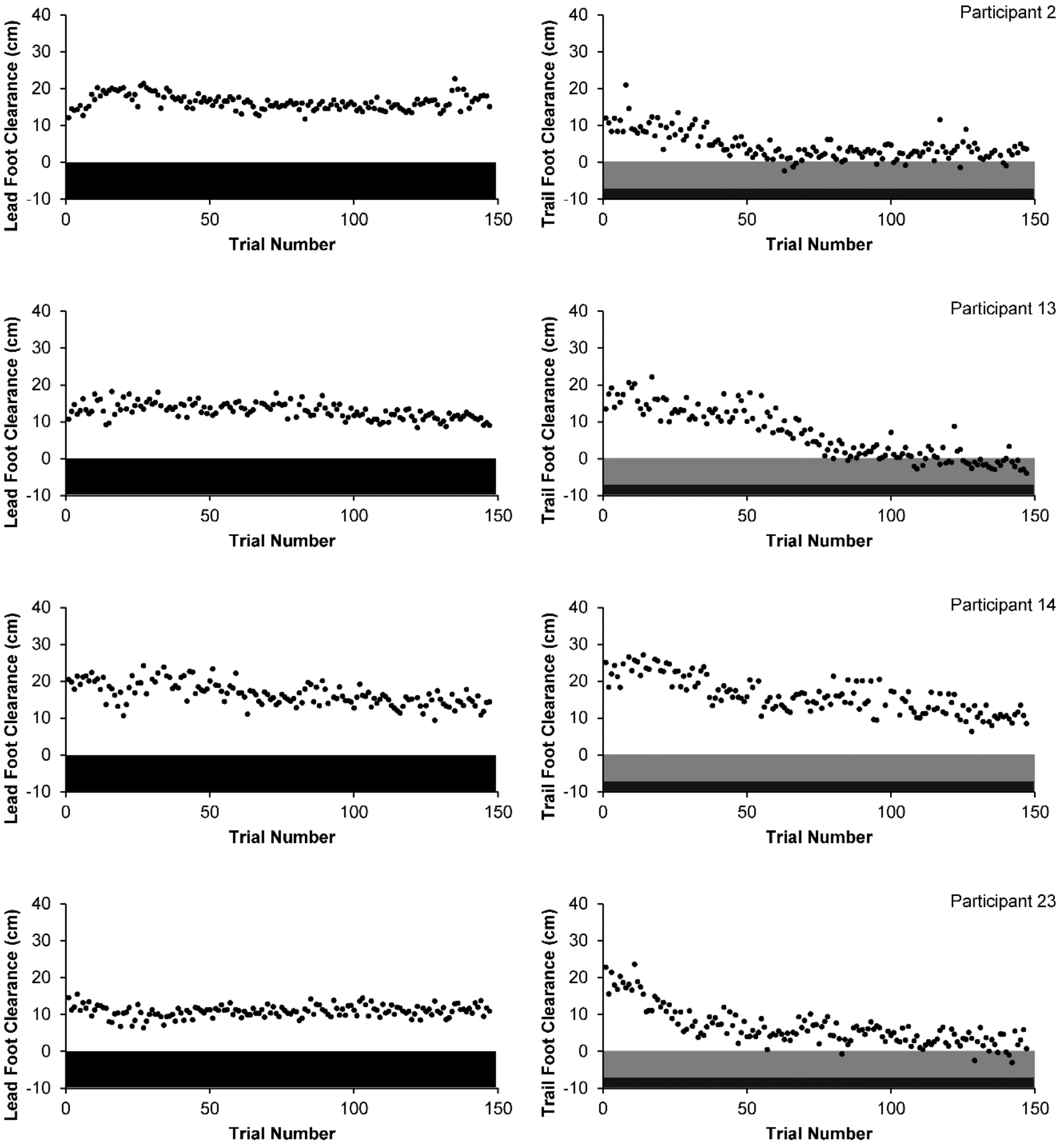

Figure 16 Foot clearance for the lead (left column) and trail (right column) limbs as a function of trial number for four participants. Foot clearance is calculated in reference to the 20 cm obstacle. Horizontal black boxes indicate real obstacle height (20 cm for the lead limb, 12.5 cm for the trail limb). Horizontal gray boxes indicate virtual obstacle for the trail limb. That is, the height that the participant observed while approaching the obstacle. Foot clearances in the gray box are virtual obstacle contacts.

Table 4 Adjusted R^2 values for each participant from the linear and exponential regressions of the trail limb. Column 4 and 5 are adjusted R^2 values for the data until visually observed behavior change (see text for further detail). Participant 9, 20, and 27 changed behavior following a flat region (*).

	Adjusted R^2		**Adjusted R^2**	
Subject	**Linear**	**Exponential**	**Linear**	**Exponential**
2	0.15	0.36	0.15	0.36
5	0.02	-0.01	0.02	-0.01
6	0.69	0.66	0.69	0.66
7	0.51	0.59	0.51	0.59
8	-0.01	-0.02	-0.01	-0.02
9*	0.65	0.64	0.65	0.70
12	0.25	0.44	0.25	0.44
13	0.81	0.75	0.81	0.75
14	0.59	0.61	0.59	0.61
15	0.27	0.31	0.27	0.31
16	0.78	0.86	0.78	0.86
17	0.36	0.53	0.36	0.53
18	0.81	0.79	0.81	0.79
19	0.42	0.43	0.42	0.43
20*	0.00	0.14	0.39	0.69
22	0.00	-0.01	0.00	-0.01
23	0.58	0.76	0.58	0.76
24	0.71	0.81	0.71	0.81
25	0.57	0.65	0.57	0.65
26	0.32	0.29	0.32	0.29
27*	0.05	0.03	0.31	0.49
Average	0.41	0.46	0.44	0.51

Table 5 Adjusted R^2 values for each participant from the linear and exponential regressions of the lead limb. Column 4 and 5 are adjusted R^2 values for the data until visually observed behavior change in the trail limb (see text for further detail). Participant 9, 20, and 27 changed trail limb behavior following a flat region (*).

	Adjusted R^2		**Adjusted R^2**	
Subject	**Linear**	**Exponential**	**Linear**	**Exponential**
2	0.05	-0.01	0.05	-0.01
5	0.17	-0.01	0.17	-0.01
6	0.05	0.10	0.05	0.10
7	0.14	0.24	0.14	0.24
8	0.19	0.47	0.19	0.47
9*	0.01	-0.02	0.35	-0.05
12	0.78	0.80	0.78	0.80
13	0.31	-0.01	0.31	-0.01
14	0.40	0.40	0.40	0.40
15	0.44	0.54	0.44	0.54
16	0.48	0.48	0.48	0.48
17	0.05	-0.02	0.05	-0.02
18	0.42	0.42	0.42	0.42
19	0.04	-0.02	0.04	-0.02
20*	0.07	-0.01	0.25	-0.04
22	0.52	0.51	0.52	0.51
23	0.01	0.06	0.01	0.06
24	-0.01	0.05	-0.01	0.05
25	0.00	-0.01	0.00	-0.01
26	0.02	0.19	0.02	0.19
27*	0.58	-0.01	0.35	-0.02
Average	0.22	0.20	0.24	0.19

7.5.5 Comparison of Gait Characteristics between Groups

Failure rates were greater for the linear than the asymptotic group (19 vs 8%, respectively; $p = 0.01$). There were no differences in lead and trail foot clearance, lead and trail foot placement, gait speed, and BMI between the linear and asymptotic groups ($p > 0.05$).

7.6 Discussion

The aim of this study was to determine if an obstacle memory can accurately guide the trail limb over an obstacle. The obstacle dropped down after the lead limb had crossed, which removed the knowledge of results (derived from somatosensory information regarding obstacle contact for the trail limb), so that the memory was not updated if the foot was too low. We predicted that foot clearance would either decrease linearly or demonstrate an asymptotic curve that gradually approached the obstacle height. Unexpectedly, both behaviors were observed: 52% demonstrated an asymptotic curve and 33% demonstrated a linear decrease; the remaining 14% demonstrated no change in foot clearance over successive trials. These findings indicate that the majority of participants had an obstacle memory that apparently became more accurate with repeated trials, and that, although the memory is accurate on average, the high variability of the trail limb foot clearance resulted in occasional failures.

The majority of the participants (N = 11; 52%) demonstrated an asymptotic curve that approached the obstacle height, which is consistent with an improvement of performance and an obstacle memory that becomes more accurate over time. This drift observed in the locomotor task has also been observed in upper limb task when visual feedback was removed (Ambike et al., 2015; Vaillancourt & Russell, 2002), which has been interpreted to indicate that the participant’s memory decays over time (Vaillancourt & Russell, 2002). However, for the majority of participants in the current obstacle crossing task, the memory did not decay over time, it became more accurate, that is, the clearance approached zero. A key difference between upper limb and lower limb tasks is that in the force production task, the participants started at the correct force level and drifted away from that value within each trial, while in the obstacle crossing task, the participant initially elevated the limb higher than necessary, and clearance drifted towards the obstacle height with repeated trials. Further, the consequence of error in the two tasks is different. There is no direct consequence if the force production drifts, however, contacting an obstacle can be destabilizing and/or embarrassing. However, in the laboratory setting, stability was not compromised following obstacle contact as the obstacle was designed to tip when contacted.

Thirty-three percent of the participants (N = 7) demonstrated a linear decrease in foot clearance. Note that 29% of these participants (N = 2; 10% of total participants) had foot clearances that remained above the actual obstacle height (e.g. participant 14 in Figure 16), but 71% had values that would result in contact if the obstacle was still in place (N = 5; 24% of total participants) (e.g. participant 13 in Figure 16). No conclusion can be drawn from the participants who linearly decreased foot clearance but remained successful, as both behaviors (asymptotic curve or continued linear decrease) could be observed if data collection had continued. However, for the 24% that dropped foot clearance values below the actual obstacle height, obstacle memory appeared to decay over time. These findings reinforce the observation that a wide variety of behavior is often observed in adaptive locomotion (Corporaal et al., 2016; Eng et al., 1994; Heijnen et al., 2014). This wide range of behaviors is especially surprising for the obstacle crossing task observed here as it seems reasonable to expect that an obstacle memory, and its ability to guide behavior, would be relatively uniform across participants. The differences in forming an obstacle memory may be related to gaze behavior. Although the same amount of information is available during the approach for each participant, participants may gather the information differently. Participants who successfully cleared the obstacle may have fixated more frequently on key aspects of the environment, which increased the opportunity to gather and process visual information about obstacle characteristics, and improved the obstacle memory (Patla & Vickers, 1997; Pontecorvo, Heijnen, Muir, & Rietdyk, 2015). The different types of behavior may also relate to the wide range in fall frequency in the field: in a 16-week period, 48% of young participants never fell, 31% fell once, and 21% fell more than once (Heijnen & Rietdyk, 2016). The participants with the linear decrease in clearance observed here, may be more likely to fall frequently in the field. The various types of behavior observed in adaptive locomotion highlight the difficulties in developing a universal fall-prevention program. Different types of locomotor behavior suggest that more individualized programs may be beneficial to reduce falls.

Trail limb failure rates with the virtual obstacle ranged from 0 to 39%, with an average failure rate of 8%. These failure rates are substantially larger than the 1-2% reported for stationary, visible obstacles (Berard & Vallis, 2006; Heijnen et al., 2012a; Mohagheghi et al., 2004; Muir et al., 2015; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006), therefore it is clear that the knowledge of obstacle contact is instrumental in guiding the limb trajectory. It seems reasonable to expect that if foot elevation is underestimated by more than 30%, as observed by some participants here, sensory information regarding limb positions would be adequate to indicate that the limb was too low on that trial, and corrections would be taken in future trials. This was apparent in the 33% of participants (N = 7) who never contacted the physical or virtual obstacle. However, it appears that the binary outcome of the task – knowledge of results derived from obstacle contact – is critical for overall performance for the majority of participants; sensory information regarding limb position alone is insufficient for most participants. This is consistent with the idea that participants are continuously exploring in order to minimize a cost function (Heijnen et al., 2012a; Loeb, 2012). Loeb (2012) argues that the participant uses the results of each trial as data to update a probability distribution of the outcome. In this study, when the outcome was not available (contact vs no contact), more exploration in the incorrect region was observed, leading to increased frequency of failures, consistent with Loeb's (2012) argument.

The difference in foot clearance between the lead and trail limb further support the argument that the limbs are controlled independently (Anstis, 1995; Heijnen et al., 2012a; Heijnen et al., 2014; Lajoie et al., 2012; Niang & McFadyen, 2004; Patla et al., 1996; Rhea & Rietdyk, 2011; Yang et al., 2004). Although the majority of participants decreased both the lead and the trail limb as a function of trial number, the behavior between the limbs was different. First, the adjusted R^2 values indicated that the lead limb decreased in a linear manner, whereas the trail limb decreased in an exponential manner for 52% of the participants. It is possible that the linear decrease in lead limb clearance may have leveled off if more trials were collected. However, a linear decrease in lead limb clearance was also observed when 250 trials were collected (Heijnen et al., 2012a). Second, for those participants who were classified as having a linear decrease in trail foot clearance, the downward slope in foot clearance was shallower for the lead than the trail limb (-0.3 vs -1.1 mm/trial for the lead and trail limb, respectively; p = 0.008).

Although this study was not set up to determine the cause of the decrease, the observed behavior did provide more insight into the possible cause(s) of the decrease in foot clearance. As suggested by Heijnen et al. (2012a), fatigue, energy minimization, attention/boredom, and exploring the region provide possible explanations for the drift in clearance. These findings provide further evidence against fatigue as a possible cause, especially for the 52% of participants who demonstrated an asymptotic curve (Figure 16, participant 2 and 23). This behavior is inconsistent with fatigue. Therefore, these findings do not support fatigue as a possible cause for the decrease in foot clearance. However, it may be that a combination of two causes is possible. Loeb argued that participants are pushing the behavior to the estimated edge of acceptable and that they are continuously exploring to keep minimizing a cost function (Loeb, 2012). In the locomotor task, this cost would most likely be energy consumption. Both energy minimization and exploring the region were disputed previously (Heijnen et al., 2012a). Energy minimization seemed unlikely because the energy expended during the recovery would be larger than the energy conserved by decreasing limb elevation and safety is regarded as paramount (Patla, 1991). However, stability is only minimally compromised in young healthy adults when participants contact the obstacle with the trail limb due to the design of the obstacle and the location of center of mass relative to the base of support. In addition, research in upper limb tasks has demonstrated that participants achieved near-optimal movements by exploration (Engelbrecht, Berthier, & O'Sullivan, 2003). Although the combination of energy minimization and exploring the region can explain the decrease in foot clearance, it is still unclear how these factors result in the large increase in foot clearance following obstacle contact (Heijnen et al., 2012a). If a participant was pushing the behavior to the edge to minimize a cost function, it would be expected that once this boundary was found, the participant would stop exploring and continue with a clearance that was successful with minimal energy expenditure.

In summary, the majority of participants (N = 11; 52%) demonstrated behavior that was consistent with an obstacle memory that became more accurate with repeated trials. Although the obstacle memory was accurate on average, a lower trail foot clearance coupled with the high variability resulted in occasional failures. Participants who progressively decreased foot clearance below the actual obstacle height (N = 5; 24%) had an obstacle memory that decayed as a function of trial number. The variety in behavior could be related to gaze behavior, as visual information regarding obstacle characteristics may be gathered differently between these two groups. The average failure rate of 8% is greater than the 1-2% observed for stationary, visible obstacles, which indicates that knowledge of obstacle contact is instrumental in guiding the limb trajectory.

CHAPTER 8. CONCLUSION

8.1 Introduction

This dissertation examined gait characteristics during inadvertent failures and systematically manipulated the sensory information available to guide the limb trajectory to determine the cause of failures and the information used to successfully guide the limbs. Young adults were used to establish a baseline obstacle crossing behavior to which balance compromised groups can be compared in the future. The emphasis of my dissertation was on inadvertent failures; three experiments were conducted to systematically examine the role of visual and somatosensory information in order to determine how this information is used to avoid obstacle contact. These studies have increased our understanding of several factors: 1) the use of an obstacle memory to guide limb trajectories, 2) why people fail to cross a stationary, visible obstacle, and 3) the independent control of the lead and trail limbs.

8.2 Obstacle Memory

When vision is unavailable to guide limb movements, there is strong support that a memory of an obstacle or target is used to guide behavior (see review in Pearson & Gramlich, 2010). The existence of an obstacle memory has been demonstrated in cats

(McVea & Pearson, 2006, 2007), horses (Whishaw et al., 2009), mice (Setogawa et al., 2014), and humans (Lajoie et al., 2012; Shinya et al., 2012). Animals have long lasting memories of obstacle characteristics like position and height, and can accurately scale trail limb trajectories when straddling an obstacle for extended periods of time. Further support for an obstacle memory is highlighted by higher failure rates in mice with working memory deficits compared to mice without deficits (Setogawa et al., 2014).

The use of an obstacle memory has also been demonstrated in this dissertation, in Chapter 5 and 7. First, when participants were asked to step over an obstacle that wasn’t physically present, termed a virtual obstacle, participants scaled both lead and trail toe peaks to the height of the virtual obstacle. These observations confirm that participants were able to rely on an obstacle memory to guide the limbs over the obstacle. Second, when participants crossed an obstacle that dropped down following lead limb crossing (which removed knowledge of results for the trail limb), 55% of participants demonstrated an asymptotic curve. This observation is consistent with the presence of an obstacle memory for the trail limb that became more accurate with repeated trials. Therefore, this dissertation extends knowledge regarding the use of obstacle memories to guide behavior: Participants were able to use a memory when vision of the obstacle was not available during approach, and when vision of the obstacle was available, they were using a memory to guide the trail limb.

8.3 Failures

Falls occur regularly in all age groups (Heijnen & Rietdyk, 2016; Rubenstein & Josephson, 2002; Talbot et al., 2005), and trips are a common event that leads to falls (Berg et al., 1997; Blake et al., 1988; Heijnen & Rietdyk, 2016; Talbot et al., 2005). Therefore, it is important to understand why the swing limb unintentionally contacts an object in the environment. Examining failures instead of successes has provided vital information regarding the cause of obstacle contact. In this dissertation, various aspects of sensory information were manipulated to determine if failures became more prevalent, in order to better understand the contribution of these sources of sensory information to guiding the limbs successfully over the obstacle.

First, the contribution of online visual information was apparent when comparing failure rates between the lead and the trail limb. Remember that online visual information is available for the lead limb, but this information is not available for the trail limb (Table 1). From the first study, discussed in Chapter 3, failure rates were lower for the lead than the trail limb (8 vs 92% for the lead and trail limb, respectively). These findings were repeated when participants stepped over the real obstacle in Chapter 5 (6 vs 94% for the lead and trail limb, respectively, determined from experiment 1 and 2 combined). The observations reported here are consistent with the literature: Lack of online visual information increased variability in trail clearance compared to the lead limb (Patla et al., 1996). Therefore, online visual information is critical and can be used to fine-tune the lead limb trajectory since the limb is visible in the lower visual field (Patla, 1998; Patla et al., 1996).

Second, the contribution of feedforward visual information was highlighted by the experiment in Chapter 5. When feedforward visual information regarding obstacle height and somatosensory information regarding obstacle contact were removed, people needed to use an obstacle memory established during preceding trial. Failure rates were 9 and 47% for the lead and trail limb, respectively. These failure rates are high, especially compared to the 1% when all sensory sources are available (Chapter 3), and 8% when somatosensory information of obstacle contact was removed (Chapter 7). These high failures rates support the findings that obstacle characteristics need to be sampled in a feedforward manner to achieve success (Mohagheghi et al., 2004; Patla, 1998; Patla & Greig, 2006). Therefore, feedforward visual information, gathered during the approach, is important to guide both limbs, but in particular the trail limb.

Finally, the contribution of somatosensory information regarding obstacle contact (knowledge of results) was apparent when somatosensory information regarding obstacle contact was removed for the trail limb (Chapter 7). Feedforward visual information gathered during the approach and online visual information of the lead limb crossing were still available to the participant. Average trail limb failure rate was 8%, which was greater than the 1% when all sensory sources were available to the participant (Chapter 3), but lower that the 47% reported when both feedforward visual information and knowledge of results were removed. Therefore, knowledge of results, provided by somatosensory information regarding obstacle contacts, is critical for overall performance. Somatosensory information regarding limb position (elevation) alone is insufficient for most participants. The finding that proprioception alone is insufficient is inconsistent with findings from Pearson and Gramlich (2010), who demonstrated that proprioception was used to update an obstacle memory in cats. The cause of the discrepancy is not readily apparent, however, it is reasonable to expect that the cats were aware of their hind limb being moved, which would cause them to modify their limb trajectory. In humans, failure rates can be calculated during obstacle crossing when foot placement is passively moved to determine if similar adjustments are made to the trajectory. Further research is needed to determine the relative contribution of somatosensory information regarding obstacle contact and limb position in human locomotion.

While most research on obstacle crossing examines the successful trials, there is a growing set of studies with failure rates quantified as a function of sensory manipulations. These studies allow a rough comparison of the relative importance of the various sources of sensory information. Since the majority of failures occur with the trail limb, this summary will focus on trail limb failures. The relatively low failure rate (1%) indicated that people are fairly successful when crossing an obstacle when all sensory information is available. Failure rates increase to 8% when somatosensory information regarding obstacle contact is removed. Failure rates are similar, at 10%, when feedforward visual information was removed 5 steps prior to crossing the obstacle (Patla, 1998). Finally, when feedforward visual information regarding obstacle characteristics was not available during approach, and somatosensory information regarding obstacle contact were removed, failure rate increased to 47%. Systematic manipulation of the sensory sources has highlighted the need of all sensory sources to successfully cross the obstacle. In particular, feedforward visual information gathered during the approach was critical, and if it was available even for a brief period, then success improved dramatically. Furthermore, knowledge of results derived from obstacle contact, provided by somatosensory information, was critical for most participants. Overall, it is apparent that all sources contribute substantially to the ability to guide the trail limb, and that visual information gathered during the approach has the largest impact on success.

8.4 Independent Control of Limbs

Although it was not the purpose of these studies, all three studies in my dissertation provide evidence in support of limb independence during adaptive locomotion. Limb independence means that the motion and/or feedback of the ipsilateral limb is not used to control the contralateral limb. First, the downward slope in foot clearance is statistically shallower for the lead than the trail limb (-0.2 vs -1 mm/trial for the lead and trail limb, respectively in Study 1 and -0.2 vs -0.8 mm/trial for the lead and trail limb, respectively in Study 3). In addition, following contact with the trail limb, trail foot clearance increased by 75%, but foot clearance of the lead limb did not change (Study 1). Second, failures rates between the lead and trail limb were substantially different. In Study 1, 92% of the contacts occurred with the trail limb. These findings were reproduced in Study 2, where trail limb contacts accounted for 90 and 100% of all physical contacts in experiment 1 and 2, respectively. In addition, 47% of the virtual contacts occurred with the trail limb, versus 9% for the lead limb. Finally, 99% of the failures occurred with the trail limb in Study 3 (physical and virtual contacts combined). If the lead limb was used to guide the trail limb, one would expect the failure rates to be similar for both limbs. Finally, although a wide variety of behavior was observed in Study 3, lead and trail limb behavior was different for the majority of participants. The lead limb appeared to decrease in a linear manner, whereas the trail limb decreased in an exponential manner for 55% of the participants. For those participants who were classified as having a linear decrease in trail foot clearance, the downward slope in foot clearance was shallower for the lead than the trail limb. If the limbs were dependent on each other during obstacle crossing, it would be expected that both limbs show similar behavior.

The findings from these three studies add to the growing body of literature that has demonstrated limb independence. Independent control of the limbs has also been shown in a variety of locomotor tasks such as steady state gait (Yang et al., 2004), adaptive locomotion (Niang & McFadyen, 2004; Patla et al., 1996), adaptive locomotion with lower visual field obstruction (Rhea & Rietdyk, 2011; Rietdyk & Rhea, 2006), and even hopping (Anstis, 1995). Furthermore, foot clearance values between the lead and the trail limb are only weakly correlated (Mohagheghi et al., 2004; Rietdyk & Rhea, 2006).

Independent control is beneficial to human locomotion, as it increases the adaptability in order to navigate safely through a cluttered environment (Patla, 1991). Inability to control the limbs independently during an obstacle crossing task may increase failure rates.

8.5 Direct Perception

Although the findings reported here generally support the concept of an obstacle memory, an obstacle memory is inconsistent with other theories of movement control, such as Gibson’s theory of direct perception (Gibson, 1966, 1979). Briefly, Gibson’s argument is that information is available in the environment and this information is picked up by the person interacting with the environment. He says that there is meaning in the light (also called the optic array) and there is no need for the brain to process this light into a meaning (as proposed by indirect perception theories). The person gathers variant properties (properties that change when viewed under different circumstances) and invariant properties (properties that do not change when viewed under different circumstances) when moving through the environment, aiding in the judgment of affordances (e.g. whether an obstacle affords stepping over). In Gibson's theory, it is important that the person is allowed to actively perceive the environment by walking through it (termed dynamic visual sampling). The importance of dynamic visual sampling in adaptive locomotion is demonstrated by a decrease in failure rates from 25% with 1.5 seconds of static visual sampling to 10% with 1.5 seconds of dynamic visual sampling (Patla, 1998), supporting Gibson's argument that more invariant properties are picked up when actively moving through the environment, leading to reduced failure rates. Gibson's ideas can be used to describe at least some of the behaviors observed in my three studies, which I will describe next.

First, the decrease in foot elevation observed first in Study 1 would be explained by the fact that more invariant properties are picked up with repeated trials. Gibson would say that the person becomes more attuned to information of a certain sort. With repeated trials, the participant may notice differences that were not noticed previously, and features become distinct that were formerly vague. This increase in visual information is used to guide the foot trajectory, which leads to a reduced foot clearance as a function of repeated trials. As discussed earlier, the decrease in foot clearance continued until contact. It can be interpreted as exploratory behavior to seek information for guiding actions. When the participant contacted the obstacle, more information was perceived about the obstacle. The participant not only received haptic information regarding obstacle contact (touch), but also received auditory information from the obstacle falling, and may have received visual information if they looked at the obstacle after contact. After gathering the information from these additional senses, the perceived risks associated with obstacle contact became clear and this information was used to adjust the limb trajectory, leading to an increase in foot clearance following obstacle contact. This could be interpreted as having an obstacle memory, as I have done repeatedly in this dissertation, but Gibson would disregard this claim of a memory and state that perception had improved through discovering new information about the obstacle. The information about the obstacle was always present, it was simply not previously detected.

The importance of gathering variant and invariant properties was highlighted by Study 2. Remember, visual information regarding obstacle height was removed and failure rates increased. Gibson states that as a person moves towards and obstacle, the background that is occluded by the obstacle is revealed and provides important information. I interpret this as the top edge of the obstacle that is used as critical information in adaptive locomotion. When the obstacle height information was removed, participants were unable to perceive the obstacle, resulting in highly variable behavior, where participants had trajectories that were too low (e.g. participant 8 and 13 in Figure 8), others had trajectories that were too high (e.g. participant 2 in Figure 8). In this case, participants were relying on a memory of obstacle characteristics, like obstacle height. Participants were able to scale trajectories to different heights, supporting the argument that they were using an obstacle memory. The use of a memory in perception is inconsistent with Gibson's theory, as he attempted to remove all cognitive processes, like memory, from perception.

Finally, in Study 3, visual information remained the same as in Study 1, but the somatosensory information regarding obstacle contact was removed. The majority of participants (55%) initially reduced foot clearance values, consistent with the argument that more invariant properties were picked up with repeated trials, and performance slowly improved. Following this initial decrease, foot clearance leveled off for the remaining trials, which can be interpreted as these participants having reached the optimal performance (i.e. foot clearance approached zero). These participant had become "experts", and picked up all the invariant properties needed to cross the obstacle. Occasional errors in trail foot clearance could be attributed to the lack of online visual information, the information that is critical to fine-tune the trajectory. The group of participant who decreased foot clearance below the actual obstacle height (18%) likely did not gather the same invariant properties as the majority of participants and/or attended to less relevant properties, leading them to adjust their behavior incorrectly. Although the same amount of information was available in the environment, Gibson would likely attribute the differences to how the participant perceived this information (i.e. the invariant properties picked up).

Gibson’s theory can also explain the highly variable behavior observed between participants in these studies. Remember the variety of behavior in Study 3, where some participants demonstrated an asymptotic curve, others demonstrated a linear decrease, and another group did not change foot clearance as a function of repeated trials. The same amount of information was available for each participant when crossing an obstacle, but participants may have gathered different amounts of information. Participants who successfully cleared the obstacle may have fixated more frequently on key aspects of the environment, which increased the opportunity to gather visual information about obstacle characteristics. This may be similar to the differences in gaze behavior between elite and near-elite athletes (Martell & Vickers, 2004; Vickers & Adolphe, 1997) and elite and rookie police officers (Vickers & Lewinski, 2012). In other words, more invariant properties were picked up by the elite performers, leading to reduced failure rates.

Although Gibson’s theory can be applied to many of my findings, there is one major inconsistency with my findings and his theory: the observation that an obstacle memory was used to guide limb trajectories. As noted earlier, memory is a cognitive activity, and in an effort to remove all cognitive activities from perception, Gibson denies the role of memory. Gibson only denies the role of memory in perception, not memory in general. His argument is that there is no role for memory in perceiving, but his theory does explain performance improvements. For example, Gibson would say that the person became more attuned to the invariant properties, and that the participant noticed differences that were not noticed previously. However, as mentioned earlier, the findings in my dissertation show that participants have an obstacle memory. The existence of an obstacle memory has also been demonstrated in cats (McVea & Pearson, 2006, 2007; Pearson & Gramlich, 2010), horses (Whishaw et al., 2009), mice (Setogawa et al., 2014), and humans (Lajoie et al., 2012; Shinya et al., 2012). In addition, the posterior parietal cortex is active during obstacle crossing (Drew et al., 2008; Lajoie et al., 2010). The importance of an obstacle memory is especially highlighted by Setogawa et al. (2014), who observed higher failure rates in mice with working memory deficits compared to control mice. To me, these findings demonstrate that cognitive processes can be associated with perception.

8.6 Future Research

This dissertation has examined failures in young adults in order to identify the behavior that results in obstacle contact. A healthy young adult population was used to establish a baseline behavior, as balance is arguably optimal in this group. The examination of failures can be extended to middle-aged adults and groups with compromised balance to identify the cause of failures in these populations. In addition, examining failures in these groups will provide information about the use of young adults in order to establish the efficacy of fall prevention programs if the cause of contact is the same between these groups.

Future research can also examine the association between kinematic gait characteristics, measured in the laboratory, and falls, in order to establish if adaptive gait characteristics assessed in the lab are related to fall-risk in young adults. Examining this association will determine if a specific adaptive locomotion task can quantify the ability to avoid falls.

Since causes of falls are multifactorial, and the laboratory task is a specific behavior, if there is a relationship, it will indicate that a simple motor task can capture a fundamental aspect of balance.

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Yogev-Seligmann, G., Rotem-Galili, Y., Mirelman, A., Dickstein, R., Giladi, N., & Hausdorff, J. M. (2010). How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability. *Physical Therapy, 90(2), 177*-186.

Yoshino, K., Motoshige, T., Araki, T., & Matsuoka, K. (2004). Effect of prolonged free-walking fatigue on gait and physiological rhythm. *Journal* of *biomechanics, 37(8), 1271*-1280.

VITA

VITA

EDUCATION

Purdue University West Lafayette, IN, USA
Doctor of Philosophy in Biomechanics May 2016
Dissertation: *Failures in Adaptive Locomotion in Young Adults*
Advisor: Dr. Shirley Rietdyk

Zuyd University Heerlen, The Netherlands
Bachelor of Applied Sciences in Medical Technology July 2010
Thesis: *Changes in Brain Dynamics Induced by Stress*
Advisor: Björn Crüts

RESEARCH EXPERIENCE

Purdue University West Lafayette, IN, USA
Ph.D. Researcher August 2010 – Present

- Examined the relationship between adaptive gait characteristics in the laboratory, and falls in the field in healthy young adults.
- Collected human movement data with a 3D motion analysis system (Optotrak, NDI, Canada) and analyzed data with MATLAB.
- Developed and administered an online survey that examined frequency and circumstances of slips, trips, and falls in the field with a daily online survey.
- Increased the understanding of why people contact an obstacle, which will advance the development of interventions to mitigate fall-risk.

BrainMarker B.V. & Nanyang Technological University Singapore, Singapore
November 2009 – April 2010
Internship

- Examined power-law scaling behavior in brain activity with the use of long-range temporal correlations as a function of stress level in young adults.
- Conducted research in a collaboration between BrainMarker B.V. and the Centre for Computational Intelligence at Nanyang Technological University, Singapore.
- Instructed graduate students from the International Islamic University Malaysia how to use the EEG software and hardware equipment to measure brain activity.

BrainMarker B.V. Buchten, The Netherlands
Internship February 2009 – June 2009

- Collaborated with BrainMarker B.V. and the Centre for Computational Intelligence at Nanyang Technological University, Singapore to transfer knowledge between disciplines in the area of electroencephalography (EEG) and data analysis techniques.
- Instructed employees of the Institute of Mental Health in Singapore to use EEG software and hardware equipment to collect brain activity in children with ADHD.

University of Bielefeld Bielefeld, Germany
Internship September 2008 – January 2009

- Collected human movement data using 3D motion analysis system (Vicon, Oxford, UK) for a variety of experiments examining arm movements in virtual reality and ping pong serve.
- Recruited subjects, collected data, and post-processed data.
- Collected gait data in stick insects with the Vicon motion capture system.

TEACHING & MENTORING EXPERIENCE

Purdue University West Lafayette, IN, USA
Teaching Assistant August 2010 – Present

- Developed and updated labs about the use of Excel, LoggerPro software, motion capture, motion analysis, electromyography, and balance for HK263 (Biomechanical Foundations of Motor Skills). Responsible for approximately 68 students per semester (total 8 semesters).

Mentoring

- Mentored over 40 undergraduate students in independent research projects (total 12 semesters).
- During recent two years, mentored new graduate students in the Biomechanics laboratory

PROFESSIONAL DEVELOPMENT

Preparing Future Faculty West Lafayette, IN, USA
The Graduate School Spring 2014

- Explored faculty roles, responsibilities, and development opportunities at different types of higher education institutions.

ACADEMIC AWARDS

Bilsland Dissertation Fellowship ($28,000) 2014 – 2015
The Bilsland Fellowship is a 12-month grant to support outstanding Ph.D. candidates in their final year of doctoral degree.

Purdue Research Foundation Research Assistantship ($28,000) 2013 – 2014
The PRF Research Grant is a 12-month award to assist Ph.D. research projects. Title: "Trip-Related Loss of Balance."

VSBFonds Scholarship. VSB Foundation (€10,000) 2010
The VSBFonds Scholarship aims to support students who demonstrate involvement in their environment to do international research.

Erasmus LifeLong Learning programme (€1,000) 2008
The Erasmus LifeLong Learning programme is a program from the European Commission to fund students for an international internship. Interned at the University of Bielefeld, Germany.

GRANTS

American Kinesiology Association Doctoral Scholar Award	2016
Carole J. Widule Award for Outstanding Graduate Scholarship ($200)	2015
Compton Graduate Research Travel Award ($500)	
Dale Hanson Award ($500)	2015
Donald L. Corrigan Professional Development Grants ($100)	2014 and 2015
Donald L. Corrigan Professional Development Grants ($375)	2015
Donald L. Corrigan Professional Development Grants ($300)	2014
	2011, 2013, and 2014

PROFESSIONAL ORGANIZATIONS

International Society of Posture and Gait Research	2012 – Present
American Society of Biomechanics	2011 – Present

SKILLS/INTERESTS

Languages:	Strong comprehension of Dutch, English, German, and Limburgs
Computer:	Proficient in MATLAB, SAS, SPSS, LabVIEW, and EndNote
Interests:	Swimming and biking

INVITED PRESENTATION

Heijnen, M.J.H. & Rietdyk, S. (2014, November). *Use of an obstacle crossing task to identify fall-risk in young adults.* Invited presentation at the Health and Kinesiology Departmental Colloquium, Purdue University, West Lafayette, IN.

SERVICE

Journal Reviewing Activities

Gait and Posture	Impact Factor 2.63
Journal of Sports Sciences	Impact Factor 2.10
BioMedical Engineering Online	Impact Factor 1.75

JOURNAL PUBLICATIONS (PEER REVIEWED)

Heijnen, M. J. H., & Rietdyk, S. (2016). Falls in young adults: perceived causes and environmental factors assessed with a daily online survey. Human movement science, 46, 86-95.

Muir, B.C., Haddad, J.M., **Heijnen, M.J.H.**, & Rietdyk, S. (2015). *Proactive gait strategies to mitigate risk of obstacle contact are more prevalent with advancing age*. Gait & posture, 41(1), 233-239. doi:10.1016/j.gaitpost.2014.10.005

Heijnen, M.J.H., Romine, N.L., Stumpf, D.M. & Rietdyk, S. (2014). *Memory guided obstacle crossing: more failures were observed for the trail limb versus lead limb.* Experimental Brain Research, 232(7), 2131-2142. doi: 10.1007/s00221-014-3903-3

Heijnen, M.J.H., Muir, B.C. & Rietdyk, S. (2012). *Factors leading to obstacle contact during adaptive locomotion.* Experimental Brain Research, 223(2), 219-231. doi: 10.1007/s00221-012-3253-y

Heijnen, M.J.H., Muir, B.C. & Rietdyk, S. (2012). *Interpolation techniques to reduce error in measurement of toe clearance during obstacle avoidance.* Journal of Biomechanics, 45(1), 196-198. doi:10.1016/j.jbiomech.2011.09.019

CONFERENCE PROCEEDINGS

Heijnen, M.J.H., Rietdyk, S. (2015) *Falls in the real world are related to obstacle crossing behaviors in a lab setting for young adults*. Poster presented at International Society for Posture & Gait Research World Congress, Seville, Spain.

Heijnen, M.J.H., Kim, A., Kim, J., Ziaie, B., Rietdyk, S. (2015) *The step width of young and middle-aged adults was substantially reduced by texting and walking*. Poster presented at International Society for Posture & Gait Research World Congress, Seville, Spain.

Pontecorvo, S.M., **Heijnen, M.J.H.**, Muir, B.C., Rietdyk, S. (2015) *Relationship between gaze behavior and failure to cross a stationary, visible obstacle*. Poster presented at International Society for Posture & Gait Research World Congress, Seville, Spain.

Kim, A., Kim, J., **Heijnen, M.J.H.**, Rietdyk, S., Ziaie, B. (2015) *Concurrent validity of a wearable smartphone-enabled camera-based system for assessment of postural sway*. Poster presented at International Society for Posture & Gait Research World Congress, Seville, Spain.

Liddy, J.J., Kim, J., **Heijnen, M.J.H.**, Kim, A., Ziaie, B. Rietdyk, S. (2015) *Reliability of multifractal detrended fluctuation analysis using smartphone technology*. Poster presented at International Society for Posture & Gait Research World Congress, Seville, Spain.

Heijnen, M.J.H., Rietdyk, S. (2014) *Failure to clear a Stationary Visible Obstacle During Gait in Older Adults.* Poster presented at 7th World Congress of Biomechanics, Boston, MA, USA.

Heijnen, M.J.H., Rietdyk, S. (2014) *Failure to clear stationary, visible obstacles is affected by surface characteristics*. Poster presented at International Society for Posture & Gait Research World Congress, Vancouver, BC, Canada.

Heijnen, M.J.H., Rietdyk, S. (2014) *Prevalence and circumstances of falls in young adults: 29% fell in a five week observation period.* Poster presented at International Society for Posture & Gait Research World Congress, Vancouver, BC, Canada.

Rietdyk, S., **Heijnen, M.J.H.**, Muir, B.C. (2014) *Failures of proactive gait adaptations: individual and environmental characteristics that result in failure to cross a visible, stationary obstacle.* International Society for Posture & Gait Research World Congress, Vancouver, BC, Canada. Podium at symposium "Proactive and Reactive Adaptations to Slips and Trips: Implications for Fall-Risk Assessment and Rehabilitation".

Muir, B.C., Rietdyk, S., Haddad, J.M., **Heijnen, M.J.H.** (2014) *The effects of advancing age on adaptive gait: a comparison of adults aged 20-25 years, 65-79 years, and 80-91 years.* Poster presented at International Society for Posture & Gait Research World Congress, Vancouver, BC, Canada.

Heijnen, M.J.H., Rietdyk, S. (2012). *A stored obstacle representation successfully guided lead limb but not trail limb trajectories during obstacle crossing.* Poster presented at the 1st Joint World Congress of ISPGR and Gait & Mental Function, Trondheim, Norway.

Heijnen, M.J.H., Muir, B.C. & Rietdyk, S. (2011). *Increased toe clearance accuracy during obstacle avoidance: validation of cubic interpolation to upsample kinematic data.* Poster presented at the 35th annual meeting of the American Society of Biomechanics, Long Beach, California, USA.

Muir, B.C., Rietdyk, S., Haddad, J.M., Seaman, J.M. & **Heijnen, M.J.H.** (2011). *The effects of balance training on obstacle crossing in older adults.* Poster presented at the 35th Annual Meeting of the American Society of Biomechanics, Long Beach, California, USA.

Heijnen, M.J.H., Muir, B.C. & Rietdyk, S. (2011). *Motor adaptation to repeated obstacle crossing during locomotion.* Poster presented at the 8th Progress in Motor Control meeting, Cincinnati, Ohio, USA.

Khosrowabadi, R., Quek, H.C., Ang, K.K., Tung, S.W. & **Heijnen, M.J.H.** (2011). *A Brain-Computer Interface for classifying EEG correlates of chronic mental stress.* Poster presented at the 2011 International joint Conference on Neural Networks, San Jose, California, USA.

Khosrowabadi, R., **Heijnen, M.J.H.**, Wahab, A. & Quek, H.C. (2010). *The Dynamic Emotion Recognition System Based on functional connectivity of brain regions.* Paper presented at the 2010 IEEE Intelligent Vehicles Symposium, San Diego, California, USA.

PUBLICATIONS

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Heijnen, M. J. H., Muir, B. C., & Rietdyk, S. (2012a). Factors leading to obstacle contact during adaptive locomotion. Experimental Brain Research, 223(2), 219-231.

Heijnen, M. J. H., Romine, N. L., Stumpf, D. M., & Rietdyk, S. (2014). Memory-guided obstacle crossing: more failures were observed for the trail limb versus lead limb. Experimental Brain Research, 232(7), 2131-2142.