Understanding the effects of obesity and age on likelihood of tripping and subsequent balance recovery

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ABSTRACT

Fall related injuries are a major public health concern due to their high associated medical costs and negative impact on quality of life. Obese and older adults are reported to fall more frequently than their normal-weight and young counterparts. To help identify potential mechanisms of these falls the purpose of the research within this dissertation was to investigate the effects of obesity and age on the likelihood of tripping and subsequent balance recovery.

Four experimental studies were conducted. The purpose of the first study was to investigate the effects of obesity, age and gender on the likelihood of tripping during level walking. Likelihood of tripping was assessed with median minimum foot clearance (MFC) and MFC interquartile range (IQR). Obesity did not increase the likelihood of tripping suggesting the increased rate of falls among obese adults is not likely due to a greater likelihood of tripping over an unseen obstacle. Additional results suggested females and individuals of shorter stature have an increased likelihood of tripping compared to their male and taller counterparts.

The purpose of the second study was two-fold. First, the effects of load carriage and ramp walking on the likelihood of tripping were investigated, followed by investigating the effects of age and obesity on the likelihood of tripping during load carriage and ramp walking. Again, likelihood of tripping was assessed with median MFC and MFC IQR. Load carriage increased the likelihood of tripping during both level and ramp walking and obesity and age increased the likelihood of tripping during selected combinations of load carriage and/or ramp walking. These results suggest that the increased rate of falls during load carriage and the increased rate of falls among obese and older adult workers reported elsewhere may be due in part to an increased likelihood of tripping.

The third study proposed a new method for investigating the likelihood of tripping as a function of obstacle height. The proposed method aimed to clear up ambiguous results often encountered when using MFC central tendency and variability to quantify likelihood of tripping. The method used trip probability curves and a statistical bootstrapping technique to compare trip probability at specific obstacle heights between groups of interest. An additional benefit of this method was that it was able to identify effects of factors not identifiable by the commonly used ANOVA analysis using MFC central tendency and variability.

The purpose of the fourth study was to investigate the effects of obesity, age and gender on balance recovery following a lab induced trip perturbation. Measures of balance recovery included fall rate, stepping strategy and characteristics, and trunk kinematics. Obese, older, and female adults fell more frequently after tripping and this higher fall rate may help explain the higher fall rates among obese, older and female adults reported elsewhere. Failed recoveries were associated with higher peak trunk angles and angular velocities in addition to the use of a lowering strategy. Obese, older, and female adults had higher peak trunk angles and angular velocities and older adults and females used lowering strategies more often. These alterations in trunk kinematics and stepping strategy may have contributed to the higher fall rate among these individuals.

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Chapter 1: Overview

1.1 Research Problem

Fall-related injuries are a major public health problem in the United States due to high associated medical costs (Bruce et al. 1992) and negative impact on quality of life (WHO 2007). Additionally, in occupational settings, falls are a significant cause of morbidity and mortality among workers (Kemmlert and Lundholm 2001, Layne and Pollack 2004, Leamon and Murphy 2010). Two major demographic trends threaten to exacerbate the scope of this problem. First, the prevalence of obesity in the U.S. has dramatically increased over the last few decades, from 22.9% in 1988-1994 to 30.5% in 1999-2000 (Flegal et al. 2002). Second, the number of adults aged 65 and over in the U.S. is projected to more than double from 2010 to 2050, to a total of 88.5 million (Vincent and Velkoff 2010). As such, the number of older and/or obese workers in the US is rapidly growing. This is problematic because individuals who are obese are reported to fall more frequently (27% vs. 15% annual fall rates) (Fjeldstad et al. 2008) and have a higher probability of sustaining fall related injuries compared to non-obese (Finkelstein et al. 2007), and adults age 65 and over experience a higher rate of annual falls (28-35%), and approximately 10-20% of these falls cause serious injuries (WHO 2007).

Although it has been shown that both age and obesity effect fall frequency, it is not clear whether the effect is due to an increased risk of losing balance, an impaired ability to recovery balance without falling or both. Several biomechanical studies have observed the effect of age and obesity on gait alterations and balance (Murray et al. 1969, Winter et al. 1990, Spyropoulos et al. 1991, Cho et al. 2003, De Vita and Hortobágyi 2003). How these alterations effect fall risk in obese and older obese adults has received little attention. We hypothesize that obesity and the age/obesity interaction will adversely affect the likelihood of falling and the ability to recover balance from a fall.

This study will focus solely on trip perturbation as they account for 35-53% of falls among older adults (Berg et al. 1997, Blake et al. 1998) and falls from tripping account for 18% of injuries and 25% of workers compensation payments (Lipscomb et al. 2006). The purpose of the study will be to assess the effects of obesity and age on the likelihood of tripping and the subsequent balance recovery. Such information is important to devise effective fall prevention strategies and to aid in the development of inclusive safety standards and engineering controls that could potentially reduce the number of occupational fall related injuries.

1.2 Document Organization

This document is organized into 7 chapters. Chapter 2 is a literature review which first examines public health concerns associated with obesity and aging then transitions to gait alterations and consequent effects on fall risk that occur in obese and older adults. The review will then specifically address measures of likelihood of tripping and the biomechanics of trip recovery in addition to reviewing several studies focused on trip related falls. Chapter 3 entitled "*Minimum foot clerance during overground walking is lower among females but not affected by obesity*" will present the first study which used human subject experiments to examine the likelihood of tripping during overground level walking. The effect of age on the likelihood of tripping during overground walking has been exhaustively studied. As such, this study focuses mainly on the effects of obesity in addition to the effects of gender which, to the best of our knowledge, has yet to be examined. Study two will be presented in Chapter 4; *"The effects of obesity and age on minimum foot clearance during occupationally relevant tasks"* where likelihood of tripping will be investigated through human subject experiments that involve simulation of occupational tasks such as load carriage, and ramp walking. Chapter 5 entitled *"A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height"* will present an original method that can be used quantify the probability of tripping as a function of obstacle height and statistically compare this probability between levels of independent variables. The final study, entitled *"Obesity and advanced age increase fall rate following a laboratory-induced trip"*, will be presented in Chapter 6. This study examines the biomechanics of trip recovery using human subject experiments. Lastly, Chapter 7 will summarize the findings and present ideas for the future direction of this research.

1.3 References

Berg, W. R., H. M. Alessio, E. M. Mills and C. Tong (1997). "Circumstances and consequences of falls in independent community dwelling older adults." Age Ageing **26**(4): 261-68.

Blake, A. J., K. Morgan, M. J. Bendall, H. Dallosso, S. B. J. Ebrahim, T. H. D. Arie, P. H. Fentem and E. J. Bassey (1998). "Falls by elderly people at home - prevalence and associated factors." Age Ageing **17**(6): 365-72.

Bruce, A. H., R. P. Fredenck and W. E. Marsha (1992). "The cost and frequency of hospitalization for fall-related injuries in older adults." American Journal of Public Health **82**(7): 1020-30.

Cho, S. H., J. M. Park and O. Y. Kwon (2003). "Gender differences in three dimensional gait analysis data from 98 healthy korean adults." Clinical Biomechanics **19**: 145-52.

De Vita, P. and T. Hortobágyi (2003). "Obesity is not associated with increased knee joint torque and power during level walking." <u>Journal of Biomechanics</u> **36**(9): 1355-62.

Finkelstein, E. A., H. Chen, M. Prabhu and J. G. Trogdon (2007). "The relationship between obesity and injuries among u.S. Adults." <u>American journal of health promotion</u> **21**(5): 460-8.

Fjeldstad, C., A. S. Fjeldstad and L. S. Acree (2008). "The influence of obesity on falls and quality of life." <u>Dynamic Medicine</u> **7**(4).

Flegal, K. M., M. D. Carroll, C. L. Ogden and L. R. Curin (2002). "Prevalence and trends in obesity among us adults, 1999-2000." <u>Journal of the American Medical Association</u> **288**(14): 1723-27.

Kemmlert, K. and L. Lundholm (2001). "Slips, trips and falls in different work groups — with reference to age and from a preventive perspective." <u>Applied Ergonomics</u> **32**(2): 149-53.

Layne, L. and K. Pollack (2004). "Nonfatal occupational injuries from slips, trips, and falls among older workers treated in hospital emergency departments, united states 1998." <u>American Journal of industrial medicine</u> **46**(1): 32-41.

Leamon, T. B. and P. L. Murphy (2010). "Occupational slips and falls: More than a trivial problem." <u>Ergonomics</u> **38**(3): 487-98.

Lipscomb, H. J., J. E. Glazner, J. Bondy, K. Guarini and D. Lezotte (2006). "Injuries from slips and trips in construction." <u>Applied Ergonomics</u> **37**(3): 267-74.

Murray, P. M., R. C. Kory and B. H. Clarkson (1969). "Walking patterns in healthy old men." <u>Journal of Gerontology</u> **24**: 169-78.

Spyropoulos, P., J. Pisciotta, C. , K. N. Pavlou, M. A. Cairns and S. R. Simon (1991). "Biomechanical gait analysis in obese men." <u>Archives of Physical Medicine and Rehabilitation</u> **72**(13): 1065-70.

Vincent, G. K. and V. A. Velkoff (2010). The next four decades: The older population in the united states : 2010-2050. U. S. DOC.

WHO. (2007). "World health orginization, global report on falls prevention in older age." Retrieved May 7, 2014, from http://www.who.int/ageing/publications/Falls_prevention7March.pdf.

Winter, D. A., A. E. Patla, J. S. Frank and S. E. Walt (1990). "Biomechanical walking pattern changes in the fit and healthy elderly " Physical Therapy **70**(6): 340-7.

Chapter 2: Introduction

2.1 Obesity and Aging: Public health concerns

Obesity is a major public health concern in the United States (U.S.). According to the World Health Organization, obesity is a disease that impairs health due to abnormal or excess body fat, and is typically defined as having a body mass index over 30 kg/m^2 (WHO 2000). Obesity is associated with numerous health conditions such as cardiovascular disease, musculoskeletal disorders, and hypertension, and the cost of health care for individuals who are obese is approximately 40% higher than those of non-obese (WHO 2000, Finkelstein et al. 2007). The prevalence of obesity in the U.S. has gone through several periods of dramatic increase. For example, prevalence increased from 22.9% in 1988-1994 to 30.5% in 1999-2000 (Flegal et al. 2002). Although this rise has begun to level off, and even decline in some demographic populations (Flegal et al. 2010, Ogden et al. 2012, Ogden et al. 2014), there is still grave public health concern as prevalence remains high. In 2011-2012 approximately 68.5% of adults were either overweight or obese ($30>BMI> 25$ kg/m^2), 34.9% were obese ($BMI> 30$ kg/m^2) and 6.4% were extremely obese (BMI> 40 kg/m2) (Ogden et al. 2014).

An additional public health concern in the U.S. is the rapid growth of the number of adults aged 65 and older. From 2000 to 2030 the population of older adults is expected to increase from 25 million to 72 million (Statistics 2012). Many health concerns that are prevalent among individuals who are obese, such as hypertension, musculoskeletal disorder and heart disease, are also widespread in older adults (Statistics 2012). This is problematic because the prevalence of obesity also increase with age (Wang and Beydoun 2007). Adults aged 60 and older have a higher odds ratio for obesity (1.35 males and 1.26 females) compared to adults aged 20-39 (Flegal et al. 2010) and although the growth in the prevalence of obesity has slowed in some demographic groups, the prevalence for women aged 60 and older still shows significant increases from 31.5 % in 2003-2004 to 38.1 % in 2011-2013 (Ogden et al. 2014).

The increasing prevalence of obesity and older adults aged 65 and older are greatly influencing labor force demographics. In the U.S. the number of obese workers increased approximately 20% between 1988-1994 and 1999-2000 (Hertz 2000), and currently 28% of workers are considered obese (Luckhaupt et al. 2014). Additionally, over the past 20 years adults over the age of 70 have shown a 3.2% (males) and 4.1% (females) increase in labor force participation (Kromer and Howard 2013). This poses an additional public health concern because individuals who are obese have a higher odds ratio (1.44) for falling in occupational settings (Swaen et al. 2014) and older adults have a higher rate of reported fall accidents (Kemmlert and Lundholm 2001).

2.2 Obesity and Aging: Falls and injury

Fall-related injuries are extremely problematic because of their high associated medical costs and negative impact on quality of life (Bruce et al. 1992). The increased risk of falls among obese and older adults is not exclusive to occupational settings. In general, individuals who are obese fall more frequently (27% vs. 15% annual fall rates) (Fjeldstad et al. 2008), and have a higher odds ratio for falling (1.12-1.34), compared to normal-weight adults (Himes and Reynolds 2012, Patino et al. 2010). Individuals who are obese are also more likely to sustain a fall-related injury compared to normal-weight counterparts (Finkelstein et al. 2007), and falls are the most common cause of hospitalization injuries among these individuals (Matter et al. 2007). Falls and fall-related injuries are also commonly associated with increased age. Approximately 28-35% of adults aged 65 and over fall each year and this increases to 32-42% for those aged 70 and over (WHO 2007) . In 2010 fall-related injuries in older adults accounted for 2.3 million emergency department visits and approximately 662,000 of these visits led to hospitalization (CDC).

2.3 Risk factors for falling

Risk factors for falling are generally classified as intrinsic or extrinsic. Where intrinsic risk factors pertain to the physical and mental status of the individual and extrinsic risk factors pertain to the interface between the individual and the environment (Close et al. 2005). Intrinsic risk factors for falls include gait and musculoskeletal alterations. Whether the gait and musculoskeletal alterations associated with obesity and aging are risk factors for falls has been paradoxical. Individuals who are obese have been shown to display several spatial and temporal gait alterations such as; a significant decrease in walking speed, step length, and step frequency in addition to a longer stance phase (Spyropoulos et al. 1991, De Vita and Hortobágyi 2003). Close *et al.* (2005) reported that decreases in all the aforementioned gait parameters are associated with an increased risk for falls (Close et al. 2005). Additionally, there are reports of decreased strength and power relative to body mass in individuals who are obese (Hulens et al. 2001, Lafortuna et al. 2005, Maffiuletti et al. 2007) and reduced muscle strength has been shown to be a significant risk factor for falling (Pijnappels et al. 2005, Rubenstein 2006, Pijnappels et al. 2008). On the other hand, obese individuals are reported to walk with a more erect posture

(De Vita and Hortobágyi 2003), have smaller hip flexion angles throughout the swing phase, greater periods of double support time (Spyropoulos et al. 1991), and increased step width (Spyropoulos et al. 1991, De Vita and Hortobágyi 2003, Ko et al. 2010) all of which are associated with an increase in dynamic stability and hence a decrease in risk of falling.

Several gait and musculoskeletal alteration in obese individuals also appear in the older adult population. Older adults have been reported to have a shorter step length, increased step width and decreased stance and double support time (Murray et al. 1969, Gillis et al. 1986, Winter et al. 1990) and there is a significant decrease in strength and power generation associated with aging (Dean et al. 2004, Savelberg and Meijer 2004, Goodpaster et al. 2006). Additionally, older obese adults have been reported to walk slower and show an increase in step width compared to older normal weight adults (Ko et al. 2010).

Extrinsic risk factors for falling include environmental hazards and performance of hazardous activities such as, uneven terrain, slippery surfaces, ramp negotiation and load carriage (Cohen and Compton 1982, Courtney and Webster 2001, Swaen et al. 2014). Many of these risk factors are common in occupational environments and contribute to the high rate of falls in occupational settings (Kemmlert and Lundholm 2001, Layne and Pollack 2004, Leamon and Murphy 2010). Fall risk increases with increasing number of risk factors. The risk of falling in community dwelling adults with no risk factors was 70% lower than those with four or more risk factors (Tinetti et al. 1988). As such, for obese and older individuals, a combination of intrinsic risk factors associated with gait and musculoskeletal alteration, and extrinsic risk factors such as those reported in occupational settings is a potential cause for concern especially considering the recent change in labor force demographics.

2.4 Likelihood of tripping

An estimated 35-53 % of falls among adults aged 65 and over are due to tripping (Berg et al. 1997, Blake et al. 1998). A common risk factor for tripping has been associated with the minimum foot clearance (MFC) between the bottom of the shoe/foot and the walking surface near mid-swing (Winter 1992). Both a smaller mean/median MFC and a higher MFC variability (e.g. standard deviation and interquartile range) are associated with an increased likelihood of tripping (Winter et al. 1990, Begg et al. 2007, Mills et al. 2008). Although not as common, the direction of skewness in a MFC distribution has also been used as an indicator of likelihood of tripping where positive skew, such that MFC values are concentrated at the lower end of the distribution, is associated with an increased likelihood of tripping (Begg et al. 2007). Additionally, a novel method has been presented by Best and Begg (2008) that utilized mean/median, MFC variability and skeweness to predict the probability of tripping at specific obstacle heights.

The effects of obesity on measures of MFC have received little attention. Individuals who are obese are reported to have altered gait kinematics such as smaller peak knee and hip flexion during the swing phase of gait, and more ankle dorsiflexion at mid-swing (Spyropoulos et al. 1991). MFC is sensitive to lower limb joint angles with most sensitivity at the ankle joint (Moosabhoy and Gard 2006) where dorsiflexion has been identified as a substantial joint motion that can increase MFC (Begg and Sparrow 2006, Moosabhoy and Gard 2006). Fundamentally, it would seem likely that obesity would affect measures of MFC. To the best of our knowledge, the only studies reporting measures of MFC in obese individuals have found no significant obesity related effects (Matrangola et al. 2011, Garman et al. 2014).

The effects of aging on measures of MFC have been studied extensively, however, results are somewhat inconsistent. Eight of nine studies reviewed by Barrett *et al.* (2010) found no age-related differences in mean/median MFC, however others have reported higher mean MFC values among older adults (Murray et al. 1969, Menant et al. 2009, Garman et al. 2014). Several studies have also reported higher MFC variability among older adults (Begg et al. 2007, Khandoker et al. 2008, Mills et al. 2008, Sparrow et al. 2008) while others have reported none [47].

MFC has also been shown to be affected by several other factors including, walking surface, gait speed, and shoe sole geometry. Walking surface has been shown to increase MFC variability, and mean/median MFC is 16-48% higher during overground walking compared to treadmill walking (Nagano et al. 2011) and 58% higher while walking over uneven terrain (Menant et al. 2009). With respect to gait speed, MFC has an increased variability (Garman et al. 2014) and mean/median MFC increases approximately 0.3-0.44 cm per every 1 m/s increase in walking speed (Schulz 2011, Garman et al. 2014). With respect to shoe characteristics, mean/median MFC increases with toe height, (the upward curvature of the shoe at the tip of the toe) (Thies et al. 2011), and heel height (Menant et al. 2009) and decrease with collar height (Menant et al. 2009).

There are issues that warrant discussion when using measures of MFC as indicators for likelihood of tripping. Indirect measures of likelihood of tripping such as mean/median MFC and MFC variability can lead to ambiguous results when both increase and decrease simultaneously. For example, reports have indicated a larger median MFC and MFC interquartile range during overground walking compared to treadmill walking (Nagano et al. 2011) and a larger median MFC and MFC interquartile range within the non-dominant leg and at faster gait speeds (Garman et al. 2014). In fact, multiple studies have reported a positive correlation between median MFC and MFC interquartile range (Begg et al. 2007, Garman et al. 2014) making ambiguous results fairly common. Begg *et al*. (2007) contributes this to a safety mechanism whereby a low median MFC will be compensated by a low interquartile range for.

Additionally, MFC only captures a single instant in time during swing, and a trip can occur at any point during the swing phase (Best and Begg 2008). MFC is traditionally used because trips occurring at the point of MFC can require greater physical demands to recover balance without falling due to the high forward velocity of the toe and the combination of the center-of-gravity location and the body's forward momentum (Winter 1992). The only study to our knowledge that has evaluated this general idea however, showed no effect of gait phase of trip on the odds ratio for falling after a trip (Pavol et al. 1999). Secondly, to the best of our knowledge, no studies have correlated MFC measures (or any measures of trip probability) with actual trip occurrence.

2.5 Trip recovery

The ability to recover balance following a trip is dependent on arresting the body's angular momentum induced by contact with a trip obstacle. Trip recovery has been examined extensively in the young adult populations (Eng et al. 1994, Grabiner et al. 1996, Schillings et al. 2000, Smeesters et al. 2001, Pijnappels et al. 2005). There are typically two recovery strategies, dependent on the phase of perturbation in the step cycle, used to counteract the body's forward rotation following a trip. Early swing perturbations typically elicit an elevating strategy in which the swing limb (perturbed limb) is lifted over the obstacle, while late swing perturbations elicit a lowering strategy in which the swing limb is rapidly placed in front of the obstacle while the contralateral stance limb is lifted over (Eng et al. 1994, Schillings et al. 2000). Mid-swing perturbations can elicit both elevating and lowering strategies (Schillings et al. 2000).

During recovery using an elevating strategy, both the stance limb (support limb) (Pijnappels et al. 2004) and swing limb (Grabiner et al. 1996) have been reported to play crucial roles in arresting the body's forward rotation. The support limb has been reported to elevate the body to increase the height of the COM thus providing time and clearance for strategic placing of the swing limb (Eng et al. 1994, Pijnappels et al. 2004). While the swing limb, upon impact, provides vertical, anterior and posterior ground reaction forces that helps retard the rotation of the entire body (Grabiner et al. 1996). This is accomplished through stance limb ankle planterflexion and extension of the hip and knee, and swing limb ankle dorsiflexion and flexion of the hip and knee (Eng et al. 1994).

Recovery using a lowering strategy involves rapid movement through inhibitory and excitatory responses (Eng et al. 1994, Schillings et al. 2000). In contrast to early swing perturbations, late swing perturbations occur when the center of mass of the body is anterior to the stance limb posing a greater threat for a fall. As such, recovery attempted using an elevating strategy (e.g. lifting the swing limb during an unstable single stance phase) during a late swing perturbation could result in a fall. Use of the lowering strategy produces a period of double support creating an intermediate position from which recovery responses can be initiated (Eng et al. 1994). As with the elevating strategy, the limb elevated over the obstacle provides ground reaction forces upon impact that assists in arresting the body's angular velocity. Common among both strategies, an essential component to recovery is reduction of trunk flexion through voluntary activation processes of the hip/trunk extensors (Grabiner et al. 1996). Although the two recovery strategies are biomechanically different they both involve a strong collaboration between all lower limb joints to arrest the body's forward rotation.

Several studies have examined risk factors associated with failed recovery following trip perturbations. Examination of gait characteristics in older adults prior to a trip perturbation revealed rapid stepping, and increased walking speed and step length are associated with an increased likelihood of falling during a trip. Step width, average trunk flexion and phase of gait showed no effect (Pavol et al. 1999). Strength and reaction time have also been shown to be a limiting factor for recovery (Schillings et al. 2000, Pavol et al. 2001, Pavol et al. 2002, Pijnappels et al. 2008). Schilling *et al.* (2000) subjected participants to trips of increasing durations. The average threshold trip duration was significantly lower in participants with decreased strength and delayed reaction time (Schillings et al. 2000). Additionally, whole leg extension strength, measured by maximum isometric push-off force, is reported to identify fallers from non-fallers during early swing perturbations (Pijnappels et al. 2008). Pavol *et al.* (2001) examined risk factors for falling specific to recovery strategy (elevating or lowering). Failed recovery eliciting a lowering strategy was associated with faster walking speed, delayed support limb loading and a more anterior head-arms-torso center of mass at the time of trip while failed recovery eliciting an elevating strategy was associated with faster walking speed, and excessive lumbar flexion (Pavol et al. 2001) .

The effects of obesity on trip recovery have received little attention. To the best of our knowledge, the only study examining the effects of obesity on trip recovery showed that rate of falls was higher and a majority of obese fallers were not able to initiate or complete the recovery step, however there was no significant increase in fall risk (Rosenblatt and Grabiner 2012). Certain factors associated with individuals who are obese would seemingly put them at a greater risk for falling. Matrangola (2011) examined single step recovery during “trip-like” perturbations. The perturbation increased the body’s forward angular velocity through an abrupt halt of a moveable platform. The maximum platform speed which balance was recovered was 13.3% lower in individuals that are obese indicating a reduced ability to recovery balance compared to normal-weight counterparts while walking at similar speeds (Matrangola 2011). Additionally, obese individual have been reported to have lower strength and power relative to body mass (Hulens et al. 2001, Lafortuna et al. 2005, Rosenblatt and Grabiner 2012) and an anterior shift in the whole body center of mass location (Corbeil et al. 2001).

The effects of aging on trip recovery have been extensive (Pavol et al. 1999, Pavol et al. 1999, Pavol et al. 2002, Van den Bogert et al. 2002, Pijnappels et al. 2004, Pijnappels et al. 2004, Pijnappels et al. 2005, Pijnappels et al. 2008, Pijnappels et al. 2008). The ability to recover balance has been shown to be lower in older adults (Pijnappels et al. 2008), with likely limiting factors of decreased strength in the lower limbs (Pavol et al. 2002, Pijnappels et al. 2008), slower rate of moment generation (Pijnappels et al. 2004), and increased response time (Van den Bogert et al. 2002, Pijnappels et al. 2004, Pijnappels et al. 2004).

2.6 Summary

The prevalence of obesity and the increase in the aging population in the U.S. is triggering a severe public health problem. Obesity and aging are associated with increased risk of falls and subsequent injuries associated with those falls. Moreover, prevalence of obesity and the increase in the aging population has caused a demographic shift in the U.S. labor force and falls are extremely prevalent and the most common cause of injuries in occupational settings. As such the safety and quality of life for obese and older adults is of grave concern. The purpose of this paper is to better understand the underlying factors related to likelihood of fall initiation and failed recovery in obese and older obese individuals leading to a possible reduction in the number of fall related injuries. This will be accomplished by examining the effects of obesity and age on likelihood of tripping during level walking (Chapter 3) and occupationally relevant tasks (Chapter 4), and creating and evaluating a new method to better quantify likelihood of tripping and increase its functionality as an aid in adjustment and development of trip-related safety standards (Chapter 5). Additionally the effects of obesity and age on balance recovery following a trip perturbation will be examined (Chapter 6) and factors associated with failed recovery will be observed. These results could potentially contribute to the development of intervention techniques to improve balance recovery in obese and older adults.

2.7 References

Begg, R., R. Best, L. Dell'Oro and S. Taylor (2007). "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls." Gait & Posture **25**(2): 191-98.

Begg, R., R. Best, L. Dell'Oro and S. Taylor (2007). "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls." Gait & Posture **25**(2): 191-98.

Begg, R. K. and W. A. Sparrow (2006). "Ageing effects on knee and ankle joint angles at key events and phases of the gait cycle." Journal of medical engineering & technology **30**(6): 382-89.

Berg, W. R., H. M. Alessio, E. M. Mills and C. Tong (1997). "Circumstances and consequences of falls in independent community dwelling older adults." Age Ageing **26**(4): 261-68.

Best, R. and R. Begg (2008). "A method for calculating the probability of tripping while walking." Journal of Biomechanics **41**(5): 1147-51.

Blake, A. J., K. Morgan, M. J. Bendall, H. Dallosso, S. B. J. Ebrahim, T. H. D. Arie, P. H. Fentem and E. J. Bassey (1998). "Falls by elderly people at home - prevalence and associated factors." Age Ageing **17**(6): 365-72.

Bruce, A. H., R. P. Fredenck and W. E. Marsha (1992). "The cost and frequency of hospitalization for fall-related injuries in older adults." American Journal of Public Health **82**(7): 1020-30.

CDC. "National center for injury prevention and control. Web–based injury statistics query and reporting system." Retrieved May 1, 2014, from http://www.cdc.gov/homeandrecreationalsafety/falls/adultfalls.html.

Close, J. C. T., S. L. Lord, H. B. Menz and C. Sherrington (2005). "What is the role of falls?" Best Practice & Research Clinical Rheumatology **19**(6): 913-35.

Cohen, H. H. and D. M. Compton (1982). "Fall accident patterns: Characterization of most frequent work surface-related injuries." Professional Saftey **6**(16-22).

Corbeil, P., M. Simoneau, D. Rancourt, A. Tremblay and N. Teasdale (2001). "Increased risk for falling associated with obesity: Mathematical modeling of postural control." Neural Systems and Rehabilitation Engineering, IEEE Transactions on **9**(2): 126-36.

Courtney, T. K. and B. S. Webster (2001). "Antecedent factors and disabling occupational morbidity-insights from the new bls data." American Industrial Hygiene Association **62**: 622-32.

De Vita, P. and T. Hortobágyi (2003). "Obesity is not associated with increased knee joint torque and power during level walking." Journal of Biomechanics **36**(9): 1355-62.

Dean, J. C., A. D. Kuo and N. B. Alexander (2004). "Age-related changes in maximal hip strength and movement speed." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **59**(3): M286-M92.

Eng, J. J., D. A. Winter and A. E. Patla (1994). "Strategies for recovery from a trip in early and late swing during human walking." Experimental Brain Research **102**: 339-49

Finkelstein, E. A., H. Chen, M. Prabhu and J. G. Trogdon (2007). "The relationship between obesity and injuries among u.S. Adults." American journal of health promotion **21**(5): 460-8.

Fjeldstad, C., A. S. Fjeldstad and L. S. Acree (2008). "The influence of obesity on falls and quality of life." Dynamic Medicine **7**(4).

Flegal, K. M., M. D. Carroll, C. L. Ogden and L. R. Curin (2002). "Prevalence and trends in obesity among us adults, 1999-2000." Journal of the American Medical Association **288**(14): 1723-27.

Flegal, K. M., M. D. Carroll, C. L. Ogden and L. R. Curtin (2010). "Prevalence and trends in obesity among us adults, 1999-2008." Journal of the American Medical Association **303**(3): 235-41.

Garman, C. R., S. L. Arena, M. A. Nussbaum, C. T. Franck and M. L. Madigan (2014). "Minimum foot clerance during overground walking is lower among females but not affected by obesity." In review (Journal of Electromyography and Kinesiology).

Gillis, B., K. Gilroy, H. Lawley, L. Mott and J. C. Wall (1986). "Slow walking speeds in healthy young and elderly females." Physiotherapy Canada **38**(6): 350-52.

Goodpaster, B. H., S. W. Park, T. B. Harris, S. B. Kritchevsky, M. Nevitt, A. V. Schwartz, E. M. Simonsick, F. A. Tylavsky, M. Visser and A. B. Newman (2006). "The loss of skeletal muscle strength, mass, and quality in older adults: The health, aging and body composition study." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **61**(10): 1059-64.

Grabiner, M. D., T. J. Koh, T. M. Lundin and D. W. Jahnigen (1996). "Kinematics of recovery from a stumble." Journal of Gerontology **48**(3): M97-M102.

Hertz, R. (2000). "Obesity in the united states workforce: Findings from the national health and nutrition examination surveys

" Retrieved May 16, 2014, from http://www.pfizer.com/files/products/Obesity_in_the_United_States_Workforce.pdf.

Himes, C. L. and S. L. Reynolds (2012). "Effect of obesity on falls, injury and disability." Journal of the American Geriatrics Society **60**(1): 124-29.

Hulens, M., G. Vansant, R. Lysens, A. Claessens, E. Muls and S. Brumagne (2001). "Study of differences in peripheral muscle strength of lean versus obese women: An allometric approach." International Journal of Obesity Related Metabolic Disorder **25**(5): 676-81

Kemmlert, K. and L. Lundholm (2001). "Slips, trips and falls in different work groups — with reference to age and from a preventive perspective." Applied Ergonomics **32**(2): 149-53.

Khandoker, A. H., S. B. Taylor, C. K. Karmakar, R. K. Begg and M. Palaniswami (2008). "Investigating scale invariant dynamics in minimum toe clerance variability of the young and elderly during treadmill walking." IEEE Trans Nerual Syst Rehabil Eng **16**(4): 380-90.

Ko, S., S. Stenholm and L. Ferrucci (2010). "Characteristic gait patterns in older adults with obesity—results from the baltimore longitudinal study of aging." Journal of Biomechanics **43**(6): 1104-10.

Kromer, B. and D. Howard (2013). "Labor force participation and work status of people 65 years and older."

Lafortuna, C. L., N. A. Maffiuletti, F. Agosti and S. A. (2005). "Gender variations of body composition, muscle strength and power output in morbid obesity." International Journal of Obesity **29**(7): 833-41.

Layne, L. and K. Pollack (2004). "Nonfatal occupational injuries from slips, trips, and falls among older workers treated in hospital emergency departments, united states 1998." American Journal of industrial medicine **46**(1): 32-41.

Leamon, T. B. and P. L. Murphy (2010). "Occupational slips and falls: More than a trivial problem." Ergonomics **38**(3): 487-98.

Luckhaupt, S. E., M. A. Cohen, J. Li and G. M. Calvert (2014). "Prevalence of obesity among u.S workers and associations with occupational factors

" American Jounral of Preventive Medicine **46**(3): 237-48.

Maffiuletti, N. A., M. Jubeau, U. Munzinger, M. Bizzini, F. Agosti, A. De Col, C. L. Lafortuna and A. Sartorio (2007). "Differences in quadriceps muscle strength and fatigue between lean and obese subjects." European Jounral of Applied Physiology **101**(1): 51-9.

Matrangola, S. (2011). An experimental and simulation based approach towards understanding the effect of obesity on blance recovery from a postural perturbation Doctorate, Virginia Tech.

Matrangola, S. L., D. E. Anderson and M. L. Madigan (2011). Preliminary investigation of slip and trip propensity in overweight and normal weight adults American Society of Biomechanics

Matter, K. C., S. A. Sinclair, S. G. Hostetler and H. Xiang (2007). "A comparison of the characteristics of injuries between obese and non-obese inpatients." Obesity (Silver Spring) **15**(10): 2384-90

Menant, J. C., J. R. Steele, H. B. Menz, B. J. Munro and S. R. Lord (2009). "Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people." Gait & Posture **29**(3): 392-97.

Mills, P. M., R. S. Barrett and S. Morrison (2008). "Toe clearance variability during walking in young and elderly men." Gait & Posture **28**(1): 101-07.

Moosabhoy, M. A. and S. A. Gard (2006). "Methodology for determining the sensitivity of swing leg toe clearance and leg length to swing leg joint angles during gait." Gait & Posture **24**(4): 493-501.

Murray, P. M., R. C. Kory and B. H. Clarkson (1969). "Walking patterns in healthy old men." Journal of Gerontology **24**: 169-78.

Nagano, H., R. K. Begg, W. A. Sparrow and S. Taylor (2011). "Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking." Clinical Biomechanics **26**(9): 962-68.

Ogden, C. L., M. D. Carroll and K. M. Flegal (2012). "Prevalence of obesity in the united states, 2009–2010." NCHS Data Brief **82**.

Ogden, C. L., M. D. Carroll, B. K. Kit and K. M. Flegal (2014). "Prevalence of childhood and adult obesity in the united states, 2011-2012." Journal of the American Medical Association **311**(8): 806-14.

Patino, C. M., R. Mckean-Cowdin, S. Azen, J. C. Allison, F. Choudhury and R. Varma (2010). "Central and peripheral visual impairment and the risk of falls and falls with injury." Ophthalmology. **117**(2): 199-206.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (1999). "Gait characteristics as risk factors for falling from trips induced in older subjects." Journal of Gerontology: Medical Sciences **54A**: M583-M81.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (1999). "The sex and age of older adults influence the outcome of induced trips." Journal of Gerontology: Medical Sciences **54A**(2): M103-08.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (2001). "Mechanism leading to a fall from an induced trip in healhty older adults "

Journal of Gerontology: Medical Sciences **56A**(7): M428-M37.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (2002). "Influence of lower extremity strength of healthy older adults on the outcome of an induced trip." Journal of American Geriatric Society **50**(2): 256-62.

Pijnappels, M., M. F. Bobbert and J. H. v. Dieën (2005). "Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers." Gait & Posture **21**(4): 388-94.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2004). "Contribution of the support limb in control of angular momentum after tripping." Journal of Biomechanics **37**(12): 1811-18.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2004). "Control of support limb muscles in recovery after tripping in young and older subjects

" Experimental Brain Research **160**(3): 326-33.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2005). "How early reactions in the support limb contribute to balance recovery after tripping." Journal of Biomechanics **38**(627-34).

Pijnappels, M., N. D. Reeves, C. N. Maganaris and J. H. van Dieën (2008). "Tripping without falling; lower limb strength, a limitation for balance recovery and a target for training in the elderly." Journal of Electromyography and Kinesiology **18**(2): 188-96.

Pijnappels, M., N. D. Reeves and J. H. van Dieën (2008). "Identification of elderly fallers by muscle strength measures." European journal of applied physiology **102**(5): 585-92.

Rosenblatt, N. J. and M. D. Grabiner (2012). "Relationship between obesity and falls by middle-aged and older women." Archives of Physical Medicine and Rehabilitation **93**(4): 718-22.

Rubenstein, L. Z. (2006). "Falls in older people: Epidemiology, risk factors and strategies for prevention." Age and ageing **35**(2): 37-41.

Savelberg, H. M. and K. Meijer (2004). "The effect of age and joint angle on the proportionality of extensor and flexor strength at the knee joint." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **59**(11): 1120-28.

Schillings, A., B. Van Wezel, T. Mulder and J. Duysens (2000). "Muscular responses and movement strategies during stumbling over obstacles." Journal of Neurophysiology **83**(4): 2093-102.

Schillings, A. M., B. M. H. van Wezel, T. Mulder and J. Duysens (2000). "Muscular responses and movement strategies during stumbling over obstacles." Journal of Neurophysiology **83**: 2093-102.

Schulz, B. W. (2011). "Minimum toe clearance adaptations to floor surface irregularity and gait speed." Journal of Biomechanics **44**(7): 1277-84.

Smeesters, C., W. C. Hayes and T. A. McMahon (2001). "The threshold trip duration for which recovery is no longer possible is associated with strength and reaction time." Journal of Biomechanics **34**(5): 589-95.

Sparrow, W. A., R. K. Begg and S. Parker (2008). "Variability in the foot-ground clearance and step timing of young and older men during single-task and dual-task treadmill walking." Gait & Posture **28**(4): 563-67.

Spyropoulos, P., J. Pisciotta, C. , K. N. Pavlou, M. A. Cairns and S. R. Simon (1991). "Biomechanical gait analysis in obese men." Archives of Physical Medicine and Rehabilitation **72**(13): 1065-70.

Statistics, N. C. f. H. (2012). Older americans 2012: Key indicators of well-being, Federal Interagency Forum on Aging Related Statistics.

Swaen, G., J. J. Burns, K. M. Collins, J. F. Bodner, B. A. Dizor and E. M. Bonner (2014). "Slips, trips and falls at a chemical manufacturing company." Occupational Medicine Advance Access

Thies, S. B., R. K. Jones, L. P. J. Kenney, D. Howard and R. Baker (2011). "Effects of ramp negotiation, paving type and shoe sole geometry on toe clearance in young adults." Journal of Biomechanics **44**(15): 2679-84.

Tinetti, M. E., M. Speechley and S. F. Ginter (1988). "Risk factors for falls among elderly persons living in the community." New England Journal of Medicine **319**(26): 1701-07.

Van den Bogert, A. J., M. J. Pavol and M. D. Grabiner (2002). "Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip." Journal of Biomechanics **35**(2): 199-205.

Wang, Y. and M. A. Beydoun (2007). "The obesity epidemic in the united states—gender, age, socioeconomic, racial/ethnic, and geographic characteristics: A systematic review and meta-regression analysis." Epidemiologic Reviews **29**(1): 6-28.

WHO (2000). Obesity: Preventing and managing the global epidemic, World Health Organization.

WHO. (2007). "World health orginization, global report on falls prevention in older age." Retrieved May 7, 2014, from http://www.who.int/ageing/publications/Falls_prevention7March.pdf.

Winter, D. A. (1992). "Foot trajectory in human gait: A precise and multifactorial motor control task." Physical Therapy **72**(1): 45-53.

Winter, D. A., A. E. Patla, J. S. Frank and S. E. Walt (1990). "Biomechanical walking pattern changes in the fit and healthy elderly " Physical Therapy **70**(6): 340-7.

Chapter 3: Minimum foot clearance during overground walking is lower among females but does not differ with obesity

3.1 Abstract

Obese adults and females are reported to fall more frequently than their normal-weight and male counterparts. To help identify potential mechanisms of these falls, this study investigated the effects of obesity and gender on minimum foot clearance during overground walking. Minimum foot clearance has been associated with the likelihood of tripping. Both young and older adults were investigated in the event that the effects of obesity and gender were affected by age. Four groups of participants (20 young normal-weight; 19 young obese; 21 older normal-weight; and 18 older obese) walked along a 10-meter walkway at a self-selected speed. Median minimum foot clearance was unaffected by obesity and age, was 21.0% lower among females, and was 24.6% higher in the non-dominant leg. There was also a positive correlation between median minimum foot clearance and body height. The interquartile range of minimum foot clearance was not affected by obesity, gender, or age, but was 72.2% higher in the non-dominant leg. These results suggest that the likelihood of tripping is not substantially influenced by obesity, but is higher among females and may contribute to their increased fall risk. Results also suggested that likelihood of tripping increases as body stature decreases.

3.2 Introduction

An estimated 27% of adults characterized as obese fall each year, compared to 15% of adults characterized as normal-weight (Fjeldstad et al. 2008). Individuals characterized as obese are also more likely to sustain a fall-related injury compared to normal-weight individuals

(Finkelstein et al. 2007), and falls are the most common cause of injuries requiring hospitalization among these individuals (Matter et al. 2007). This is problematic because the prevalence of obesity in the U.S. has dramatically increased over the last few decades, from 22.9% in 1988-1994 to 30.5% in 1999-2000. The higher rate of falls among obese individuals may be due to altered gait kinematics increasing the likelihood of tripping (Spyropoulos et al. 1991, Cho et al. 2003, Ko et al. 2010). For example, obese adults exhibit a decrease in walking speed, and step length (De Vita and Hortobágyi 2003, Lai et al. 2008, Ko et al. 2010) in addition to smaller knee and hip flexion angles throughout the swing phase of gait, and greater ankle dorsiflexion at mid-swing (Spyropoulos et al. 1991). Gait speed, and hip, knee, and ankle angles influence the minimum foot clearance (MFC) during the swing phase of gait (Schulz 2011). MFC has been associated with the likelihood of tripping, with a smaller mean/median MFC and a higher MFC variability (e.g. standard deviation and interquartile range) both being associated with an increased likelihood of tripping (Winter et al. 1990, Begg et al. 2007, Mills et al. 2008). To our knowledge, no studies have directly investigated the effects of obesity on MFC.

Females are 58% more likely than males to suffer a nonfatal fall-related injury (Ambrose et al. 2013), and females 65 years and older account for 71% of emergency department visits for unintentional fall injuries (Stevens 2005). As with obesity, this higher rate of falls may be due, in part, to an increased likelihood of tripping. Gender differences in gait have been inconsistently reported in the literature (Nigg et al. 1994, Kerrigan et al. 1998, Cho et al. 2003). Cho et al (2004) reported that females walked significantly slower than males and expended less energy for propulsion during push off, whereas Kerrigan et al. (1998) showed equivalent gait speed and greater propulsive energy during push off in addition to greater hip flexion and less knee extension prior to foot strike. As such, it is unclear if MFC differs between genders.

The purpose of this study was to investigate the effects of obesity and gender on MFC during overground walking. Because an estimated 35-53% of falls among older adults aged 65 and over are due to tripping (Berg et al. 1997, Blake et al. 1998), and the effects of obesity and gender may differ with age, we included both young and older adults. Effects of body height, leg, and gait speed were also investigated based upon their potential to influence the differences related to obesity and gender. We hypothesized: 1) obese adults would exhibit a smaller MFC than normal-weight adults, and 2) females would exhibit a smaller MFC and/or greater within-subject MFC variability. These hypotheses were based upon previously reported gait alterations associated with obesity, and evidence indicating a higher rate of falling among individuals who are obese and females. Results from this study can help determine whether the previously-reported higher rate of falls among obese adults and females is related to a greater likelihood of tripping.

3.3 Methods

Seventy-eight participants completed the study including 20 young (age 18-30 years) normal-weight (body mass index, or BMI 18-24.9 kg/m^2) adults, 19 young obese (BMI 30-40 kg/m^2) adults, 21 older (age 60-80 years) normal-weight adults, and 18 older obese adults (Table 1). Participants were recruited from the university and local community populations using paper and electronic advertisements. None of the participants reported experiencing more than a 2.3 kg change in body mass over the six months prior to testing, or any musculoskeletal, neurological, or balance disorders that affected their gait. The study was approved by the university

Institutional Review Board, and all participants provided written informed consent prior to participation.

Table 3.1: Participant demographics, gait speed and step length (mean ± standard deviation). Note: NW = normal-weight group, OB = obese group, F = female, M = male

	Young		Older	
	NW	OB	NW	OB
Sample Size	F: (n=10) M: (n=10)	F: (n=9) M: (n=10)	F: (n=6) M: (n=8)	F: (n=5) M: (n=6)
Age (years)	F: 24.4 ± 3.4 M: 23.8 ± 3.2	F: 24.8 ± 2.8 M: 21.9 ± 2.5	F: 66.8 ± 4.9 M: 65.8 ± 4.6	F: 65.6 ± 5.5 M: 74.3 ± 6.1
BMI (kg/m^2)	F: 23.1 ± 2.2 M: 21.2 ± 1.7	F: 34.0 ± 3.5 M: 33.2 ± 3.1	F: 23.8 ± 2.0 M: 24.5 ± 1.4	F: 33.1 ± 2.0 M: 31.5 ± 1.7
Height (cm)	F: 166.8 ± 6.0 M: 175.4 ± 4.7	F:163.9 ± 4.8 M: 178.3 ± 5.6	F: 161.4 ± 8.1 M: 179.6 ± 8.1	F: 163.7 ± 11.6 M: 178.6 ± 8.3
Gait Speed (m/s)	F: 1.31 ± .18 M: 1.26 ± .14	F: 1.26 ± .26 M: 1.30 ± .16	F:1.34 ± .18 M:1.36 ± .22	F:1.21 ± .06 M:1.21 ± .15
Step Length (cm)	F: 64.2 ± 5.2 M: 63.0 ± 5.3	F: 61.0 ± 3.3 M: 66.0 ± 4.9	F: 64.1 ± 5.2 M: 67.4 ± 6.6	F: 58.8 ± 2.7 M: 65.7 ± 4.8

Participants completed a single experimental session involving eight walking trials. These trials were done at a self-selected speed on a 10-meter walkway covered in vinyl tiles. Analysis of each walking trial used data from the swing phases of both the dominant and non-dominant legs. Thus, 16 swing phases were analyzed from each participant. At no point during the experiment were participants told there was a chance they would be perturbed to elicit a fall (i.e., tripped or slipped), and all participants wore the same brand of athletic shoes in their requested size.

The positions of four reflective markers on each shoe were sampled at 100 Hz using a six-camera motion analysis system (MX-T10, Vicon Motion Systems Inc., L.A, CA), and these were subsequently low-pass filtered at 5 Hz (8th-order, zero-phase-shift Butterworth filter). MFC during each swing phase was determined using a method adopted from Startzell et al (1999). Prior to walking trials, a pointer with three non-collinear markers was used to define approximately 13 virtual points traversing the perimeter of each shoe sole within a shoe-fixed Cartesian reference frame. Positions of these virtual points were then transformed into an inertial (global) reference frame. MFC was defined as the lowest of these points near the middle of swing (Figure 1). For all walking trials, the location on the shoe at which MFC occurred was within the anterior half of the sole. The median MFC (MFC_{Med}) and MFC interquartile range (MFC_{IQR}) were determined for each participant over the eight separate swing phases of each leg. Gait speed in each trial was determined a passive reflective marker on the medial border of the right scapula.

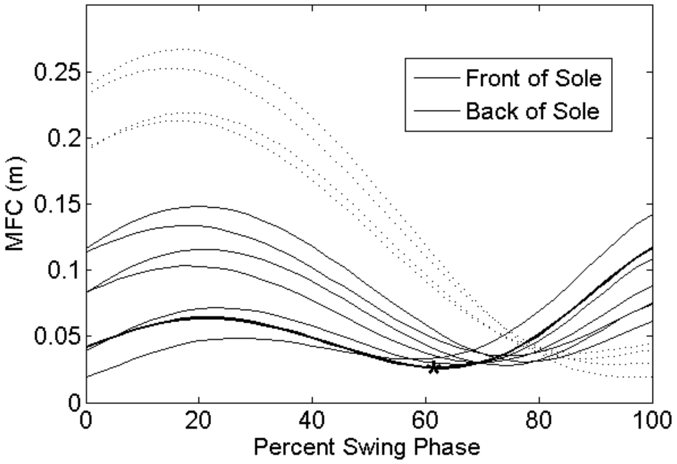

Figure 3.1: Foot clearance for all virtual points on the sole of the shoe for a single representative swing phase. Dashed and solid lines represent virtual points on the back and front of the respectively. The bold line represents the trajectory of the virtual point that yielded the lowest value of MFC (indicated by the symbol *).

A four-way, mixed-factor analysis of covariance was performed on MFC_{Med} and MFC_{IQR} using JMP v10 (SAS, Cary, NC) with significance concluded when $p \leq 0.05$. Categorical independent variables were obesity (obese or normal-weight), gender, age (young or older), and leg (dominant or non-dominant), and both gait speed and body height were included as covariates. MFC_{IQR} was log-transformed in order to achieve normally distributed residuals. Initially, two statistical models were created for each MFC measure, one including all two-way and three-way interactions, and another including only two-way interactions. Root-mean-square errors of these two models differed by less than 0.006 cm for MFC_{Med} and less than 0.002 cm for MFC_{IQR}, indicating little improvement in model fit when including the three-way interactions. As such, the simpler models (i.e., with only two-way interactions) were used for subsequent analysis to facilitate results interpretation. Iterative backwards elimination was then used to remove non-significant two-way interactions until only main effects and significant two-way interactions remained in the final model. Following this procedure, the only significant interaction was an age x height interaction for MFC_{Med}. Finally, a bivariate correlation analysis was used to assess the relationship between MFC_{Med} and MFC_{IQR}.

3.4 Results

MFC_{Med} was unaffected by obesity ($p = 0.567$) and age ($p = 0.151$), but was 21.0% lower among females ($p = 0.002$) and 24.6% higher in the non-dominant leg ($p < 0.001$; Table 2). MFC_{Med} also increased 0.22 cm for every 10 cm increase in body height among older adults ($p=0.027$), and this relationship approached significance among young adults ($p = 0.071$).

$\mathrm{MFC_{IQR}}$ was not affected by obesity (p=0.865), gender (p = 0.127), or age (p = 0.596), but was 72.2% higher in the non-dominant leg (p<0.001; Table 2). The effect of gait speed on $\mathrm{MFC_{IQR}}$ approached significance (p < 0.068), with $\mathrm{MFC_{IQR}}$ increasing 0.47 cm for every 1 m/s increase in speed. $\mathrm{MFC_{Med}}$ and $\mathrm{MFC_{IQR}}$ were positively correlated (r = 0.45; p <0.001) with $\mathrm{MFC_{IQR}}$ increasing 0.2 cm for every 1 cm increase in $\mathrm{MFC_{Med}}$.

Table 3.2: Least squares means (95% confidence interval) of MFC.

		$\mathrm{MFC_{Med}}$ (cm)	p-value	$\mathrm{MFC_{IQR}}$ (cm)
Obesity	Normal-Weight	2.53 (2.34,2.73)	0.567	0.57 (0.50,0.65)
	Obese	2.46 (2.25,2.66)		0.56 (0.48,0.64)
Age	Young	2.39 (2.21,2.57)	0.145	0.55 (0.49,0.62)
	Old	2.60 (2.38,2.82)		0.58 (0.50,0.67)
Gender	Male	**2.80 (2.57,3.03)**	**0.003**	0.62 (0.53,0.72)
	Female	**2.19 (1.94,2.44)**		0.51 (0.43,0.60)
Leg	Non-Dominant	**2.78 (2.60,2.93)**	**< 0.001**	**0.74 (0.66,0.84)**
	Dominant	**2.23 (2.06,2.40)**		**0.42 (0.38,0.48)**

3.5 Discussion

The purpose of this study was to investigate the effects of obesity and gender on MFC during overground walking. Our first hypothesis was that obese adults would exhibit a smaller MFC than normal-weight adults. This hypothesis was not supported since the differences between groups was both non-significant and relatively small. The lack of an effect of obesity on $\mathrm{MFC_{Med}}$ was unexpected because individuals who are obese typically walk slower (De Vita and Hortobágyi 2003), and with less hip and knee flexion during swing (Spyropoulos et al. 1991), and these differences should lead to smaller values of $\mathrm{MFC_{Med}}$ (Moosabhoy and Gard 2006, Schulz 2011). However, individuals who are obese also exhibit a more dorsiflexed ankle angle during mid-swing (Spyropoulos et al. 1991), which would be expected to increase MFC_{Med}. This latter effect may have counteracted the influence of reduced hip and knee flexion during swing. Joint angles, though, were not measured here. Our second hypothesis was that females would exhibit a smaller MFC and/or greater within-subject variability. This hypothesis was supported in that females exhibited a smaller MFC_{Med}, which suggested an increased likelihood of tripping compared to males. This smaller MFC_{Med} may be due, at least in part, to the gender differences in gait previously mentioned.

When comparing to other studies that also investigated overground walking, the mean MFC_{Med} of 2.4 cm reported here among young adults was similar to the 2.9 cm reported by (Thies et al. 2011) and 2.8 cm reported by (Menant et al. 2009), but was substantially larger than the 1.29 cm reported by (Winter et al. 1990) and 1.22 cm reported by (Nagano et al. 2011). MFC_{Med} values of 1.29-1.49 cm reported for treadmill walking (Begg et al. 2007, Khandoker et al. 2008, Mills et al. 2008) are consistently lower than those measured in the present study. These discrepancies may be due to 1) MFC being 16-48% larger during overground walking compared to treadmill walking (Nagano et al. 2011), and/or 2) the height of the toe of the shoe used in the present study being rather large (3.5 cm), which can increase MFC_{Med} (Thies et al. 2011). The mean MFC_{IQR} of 0.68 cm reported here for young adults was similar to values of 0.6-0.9 cm reported during overground walking (Thies et al. 2011) and 0.32-0.96 cm during treadmill walking (Begg et al. 2007).

Decreasing body height was associated with a decrease in $\mathrm{MFC}_{\mathrm{Med}}$. In particular, $\mathrm{MFC}_{\mathrm{Med}}$ decreased 0.02 cm for every 1 cm decrease in body height. This translates to a 0.91 cm difference in $\mathrm{MFC}_{\mathrm{Med}}$ between the participants in the current study with maximum and minimum body height due to this relationship alone. In retrospect, this association seems intuitive if individuals of varying height walk with similar joint angles. To illustrate, static models of the two participants in the current study with the maximum and minimum body height (Figure 2) were constructed using segment lengths proportional to body height (de Leva 1996). If both models are positioned with identical joint angles that approximate the instant of MFC (Moosabhoy and Gard 2006), the MFC is 4.13 cm higher in the tallest participant. Although the static models reveal a substantially larger effect of body height than predicted by our statistical model and all of our data, it is based upon only two participants, and joint angle positions were approximated from the literature. However, it serves to illustrate the effect of height in a simplified manner and, consistent with our experimental results, suggests that individuals of shorter stature may be at a greater likelihood of tripping.

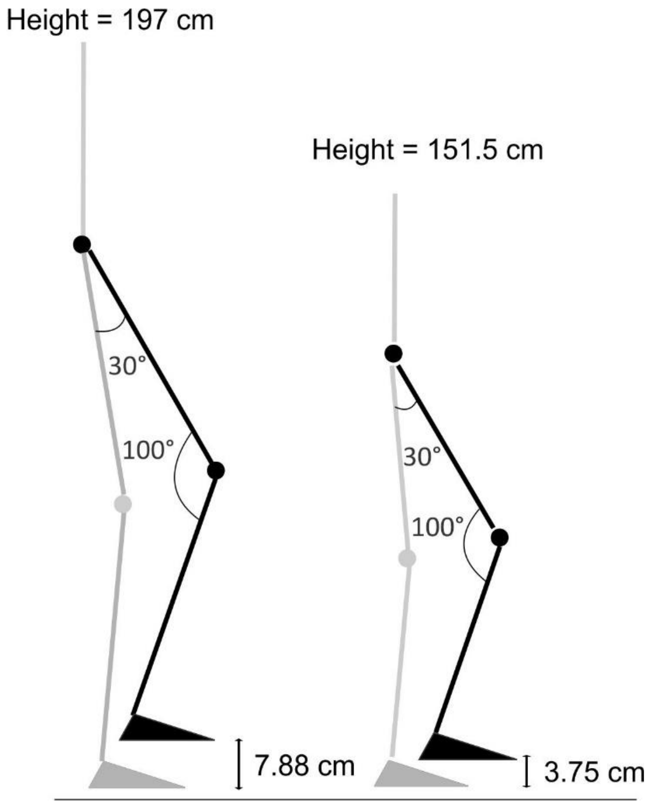

Figure 3.2: Sagittal plane view of two stick-figure models with heights representing the tallest (height of 197 cm) and shortest (height of 151.5 cm) participants in the current study. Segment lengths were calculated from Dempster et al. (1967) and joint angles at the time of MFC were taken from Levinger et al. (2012). This illustration demonstrates that a 45.5 cm change in height results in a 4.13 cm change in MCF.

Prior studies have reported significant effects of age, leg, and gait speed on MFC. The lack of an effect of age in the current study was consistent with the majority of reports reviewed by Barrett et al. (2010), but inconsistent with studies by Menant et al. (2009) and Murray et al. (1969) who both reported a higher MFC_{Med} among older adults. The lack of an effect of age on MFC_{IQR} in the present study was inconsistent with a 17.3-39.5% higher MFC_{IQR} reported earlier among older adults (Begg et al. 2007). These prior studies, however, evaluated MFC_{IQR} during treadmill walking, and it is plausible that the higher kinematic variability during overground walking versus treadmill walking (Dingwell et al. 2001) made it more difficult to detect age-related differences in MFC_{IQR} during overground walking. Regarding the effect of leg, the 24.6% higher MFC_{Med} in the non-dominant leg found here was consistent with a 40% difference reported by Nagano et al. (2011) for older adults during treadmill walking, but no studies to our knowledge have investigated the effects of leg on MFC_{IQR} during overground walking. It has been speculated that humans generally use their dominant leg for mobilization and the non-dominant leg for postural stabilization (Sadeghi et al. 2000). Such an asymmetry could account for some of the differences in MFC_{Med} and MFC_{IQR} found here between legs.

A decrease in MFC_{Med} and an increase in MFC_{IQR} are each associated with an increase in the likelihood of tripping (Winter et al. 1990, Begg et al. 2007, Mills et al. 2008). An increase in both values, though, ostensibly gives an ambiguous indication of likelihood of tripping. Our results indicated a larger MFC_{Med} and larger MFC_{IQR} within the non-dominant leg. As such, it is unclear how the likelihood of tripping might differ between legs. Additional ambiguity arises from the positive correlation between MFC_{Med} and MFC_{IQR} found here and elsewhere (Begg et al. 2007). Further investigation is needed to better understand how MFC_{Med} and MFC_{IQR} quantitatively affect the likelihood of tripping, both independently and together.

Several limitations to this work warrant mention. First, the method used to calculate MFC assumed that the shoe is a rigid body. While this is clearly not true, it was considered reasonable during swing when no external forces were applied to the shoe. Second, and as with any cross-sectional study, other differences between groups besides the characteristics reported here could have contributed to the results. Lastly, the sample size for this analysis was small compared to studies that employed treadmill walking, and may have made it more difficult to identify three-way interactions.

3.6 Conclusion

Our results suggest that there is no substantial influence of obesity on the likelihood of tripping, specifically trip initiation, during overground walking. As such, the higher rate of falls among individuals who are obese does not appear to be due to a greater likelihood of tripping. Our results also suggest an increased likelihood of tripping among females and individuals of shorter stature.

3.7 Acknowledgments

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3.8 References

Ambrose, A. F., G. Paul and J. M. Hausdorff (2013). "Risk factors for falls among older adults: A review of the literature." Maturitas **75**(1): 51-61.

Begg, R., R. Best, L. Dell'Oro and S. Taylor (2007). "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls." Gait & Posture **25**(2): 191-98.

Berg, W. R., H. M. Alessio, E. M. Mills and C. Tong (1997). "Circumstances and consequences of falls in independent community dwelling older adults." Age Ageing **26**(4): 261-68.

Blake, A. J., K. Morgan, M. J. Bendall, H. Dallosso, S. B. J. Ebrahim, T. H. D. Arie, P. H. Fentem and E. J. Bassey (1998). "Falls by elderly people at home - prevalence and associated factors." Age Ageing **17**(6): 365-72.

Cho, S. H., J. M. Park and O. Y. Kwon (2003). "Gender differences in three dimensional gait analysis data from 98 healthy korean adults." Clinical Biomechanics **19**: 145-52.

de Leva, P. (1996). "Adjustments to zatrsiorsky-seluyanovs's segment inertia parameters." Journal of Biomechanics **29**(9): 1223-30.

De Vita, P. and T. Hortobágyi (2003). "Obesity is not associated with increased knee joint torque and power during level walking." Journal of Biomechanics **36**(9): 1355-62.

Dingwell, J. B., J. P. Cusumano, P. R. Cavanagh and D. Sternad (2001). "Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. ." Journal Biomechanical Engineering **123**(1): 27-32.

Finkelstein, E. A., H. Chen, M. Prabhu and J. G. Trogdon (2007). "The relationship between obesity and injuries among u.S. Adults." American journal of health promotion **21**(5): 460-8.

Fjeldstad, C., A. S. Fjeldstad and L. S. Acree (2008). "The influence of obesity on falls and quality of life." Dynamic Medicine **7**(4).

Kerrigan, D. C., M. K. Todd, D. C.U., L. A. Lipsitz and J. J. Collins (1998). "Biomechanical gait alterations independent of speed in the healthy elderly: Evidence for specific limiting impairments." Archives of Physical Medicine and Rehabilitation **79**(3): 317-22.

Khandoker, A. H., S. B. Taylor, C. K. Karmakar, R. K. Begg and M. Palaniswami (2008). "Investigating scale invariant dynamics in minimum toe clerance variability of the young and elderly during treadmill walking." IEEE Trans Nerual Syst Rehabil Eng **16**(4): 380-90.

Ko, S., S. Stenholm and L. Ferrucci (2010). "Characteristic gait patterns in older adults with obesity—results from the baltimore longitudinal study of aging." Journal of Biomechanics **43**(6): 1104-10.

Lai, P. P., A. K. Leung, A. N. Li and M. Zhang (2008). "Three-dimensional gait analysis of obese adults." Clinical Biomechanics **23**: s2-s6.

Matter, K. C., S. A. Sinclair, S. G. Hostetler and H. Xiang (2007). "A comparison of the characteristics of injuries between obese and non-obese inpatients." Obesity (Silver Spring) **15**(10): 2384-90

Menant, J. C., J. R. Steele, H. B. Menz, B. J. Munro and S. R. Lord (2009). "Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people." Gait & Posture **29**(3): 392-97.

Mills, P. M., R. S. Barrett and S. Morrison (2008). "Toe clearance variability during walking in young and elderly men." Gait & Posture **28**(1): 101-07.

Moosabhoy, M. A. and S. A. Gard (2006). "Methodology for determining the sensitivity of swing leg toe clearance and leg length to swing leg joint angles during gait." Gait & Posture **24**(4): 493-501.

Nagano, H., R. K. Begg, W. A. Sparrow and S. Taylor (2011). "Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking." Clinical Biomechanics **26**(9): 962-68.

Nigg, B. M., V. Fisher and J. L. Ronsky (1994). "Gait characteristics as a function of age and gender." Gait & Posture **2** 213-20.

Sadeghi, H., P. Allard, F. Prince and H. Labelle (2000). "Symmetry and limb dominance in able-bodied gait: A review." Gait & Posture **12**(1): 34-45.

Schulz, B. W. (2011). "Minimum toe clearance adaptations to floor surface irregularity and gait speed." Journal of Biomechanics **44**(7): 1277-84.

Spyropoulos, P., J. Pisciotta, C. , K. N. Pavlou, M. A. Cairns and S. R. Simon (1991). "Biomechanical gait analysis in obese men." Archives of Physical Medicine and Rehabilitation **72**(13): 1065-70.

Stevens, J. A. (2005). "Gender differences for non-fatal unnintentional fall related injuries among older adults " Injury Prevention **11**: 115-19.

Thies, S. B., R. K. Jones, L. P. J. Kenney, D. Howard and R. Baker (2011). "Effects of ramp negotiation, paving type and shoe sole geometry on toe clearance in young adults." Journal of Biomechanics **44**(15): 2679-84.

Winter, D. A., A. E. Patla, J. S. Frank and S. E. Walt (1990). "Biomechanical walking pattern changes in the fit and healthy elderly " Physical Therapy **70**(6): 340-7.

Chapter 4: The effects of obesity and age on minimum foot clearance during occupationally relevant tasks

4.1 Abstract

Obese and older adult workers are reported to fall more frequently than their normal-weight and young counterparts. Anterior load carriage and ramp negotiation are occupational tasks commonly associated with these falls. To help identify potential mechanisms for these falls the likelihood of tripping during load carriage and ramp walking, and the effects of obesity and age on the likelihood of tripping during these tasks was investigated. Likelihood of tripping was assessed through median minimum foot clearance (MFC) and minimum foot clearance interquartile range (IQR). Four groups of participant (nine young normal-weight, eight young obese, nine older normal-weight, and eight older obese adults) completed the study. Compared to level walking without load carriage, median MFC was 16% lower during ramp ascent with load carriage, and MFC IQR was 71% higher during level walking with load carriage, and 53% higher during ramp descent with load carriage. During ramp descent, MFC IQR was 140% higher among older compared to young adults and during ramp ascent with load carriage MFC IQR was 108% higher among normal-weight older compared to normal-weight young adults, and 96% higher among young obese adults compared to young normal-weight adults . These results suggest load carriage increases the likelihood of tripping during both level and ramp walking and obesity and age increase the likelihood of tripping during selected combinations of load carriage and/or ramp walking.

4.2 Introduction

Occupational slips, trips, and falls are significant economic and societal issues in the United States (Kemmlert and Lundholm 2001, Layne and Pollack 2004, Leamon and Murphy 2010), costing approximately $70 billion and accounting for 15% of all occupational fatalities annually (Saftey 2012). Of all industries, the construction industry experiences the most fall-related mortalities (U.S. Bureau of Labor Statistics 2009), and within this industry falls are the leading cause of work-related deaths (CPWR 2007). Labor force demographics in the U.S. have changed dramatically over the past few decades. A reported 28% of workers are considered obese (Luckhaupt et al. 2014), which is a 20% increase over past ten years (Hertz 2000), and 4.7% of workers are 65 and older, which is a 10% increase over the past twenty years (Kromer and Howard 2013). This is problematic because obese and older adult workers have higher rates of fall accidents in occupational settings (Kemmlert and Lundholm 2001, Ambrose et al. 2013, Swaen et al. 2014).

Falls from tripping account for 18% of injuries and 25% of workers compensation payments (Lipscomb et al. 2006). The likelihood of tripping has been associated with the minimum foot clearance (MFC) between the bottom of the shoe/foot and the walking surface near mid-swing of the gait cycle. Both a smaller mean/median MFC and a higher MFC variability (e.g. standard deviation or interquartile range) are associated with an increased likelihood of tripping (Winter 1992, Begg et al. 2007, Mills et al. 2008). Advanced age can increase MFC variability, but does not affect mean/median MFC (Barrett et al. 2010). Obesity has not been shown to affect MFC during level walking (Garman et al. 2014), but has received limited attention.

The performance of occupationally-relevant tasks such as load carriage and ramp walking increases susceptibility and severity of fall-related injuries. Load carriage is involved in approximately 30% of occupational falls (Courtney and Webster 2001) and exhibits an odds ratio of 3.0 for falling (Swaen et al. 2014). Similarly, ramp walking is involved in approximately 12% of falls (Cohen and Compton 1982). These falls may be due, in part, to an increased likelihood of tripping. Prior work has been inconsistent with respect to the effect of ramp walking on MFC parameters. Some studies have revealed a higher MFC during ramp ascent compared to level walking (Prentice, Hasler et al. 2004, Thies, Jones et al. 2011), while others have revealed a lower MFC during ramp ascent (Khandoker et al. 2010). There is, however, a general agreement that MFC values are higher during ramp descent compared to level walking (Khandoker et al. 2010, Thies et al. 2011). Anterior load carriage has not been found to affect median MFC (Rietdyk et al. 2005, Shultz et al. 2009).

The perceived difficulty of a task (Niechwiej-Szwedo et al. 2007) and the visual obstruction of the foot/floor interface affects stepping variability (Rhea and Rietdyk 2007, Schulz et al. 2010). Ramp walking increases joint moments in the lower limbs, and thus task difficulty, especially in populations with strength or neuromuscular limitations (Redfern and DiPasquale 1997). Older adults have reduced strength compared to young adults (Goodpaster et al. 2006), and obese adults have reduced relative strength and power compared to normal-weight adults (Hulens et al. 2001, Lafortuna et al. 2005, Rosenblatt and Grabiner 2012). As such, tasks such as ramp walking that have higher strength demands than level walking, or load carriage that obstructs the view of the foot/floor interface during walking, may be more difficult for older and obese adults. This may increase gait variability, MFC variability, and thus increase likelihood of tripping.

The primary goal of this study was to investigate the effects of load carriage and ramp walking on the likelihood of tripping. The secondary goal was to investigate the effects of obesity and age on the likelihood of tripping during load carriage and ramp walking. Two hypotheses were posed. First, ramp walking, load carriage, and/or ramp walking with load carriage will increase the likelihood of tripping compared to level walking. Second, obesity and age will increase the likelihood of tripping during load carriage, ramp walking, and/or ramp walking with load carriage. The likelihood of tripping will be quantified using MFC. Results from this study can help identify tasks and/or personal characteristics associated with an increased risk of tripping during occupational work, and could motivate the development of more inclusive safety standards for the increasing population of obese and/or older adult workers.

4.3 Methods

Thirty-four male participants completed the study including nine young (age 18-30 years) normal-weight (body mass index, or BMI, of 18-24.9 kg/m^2) adults, eight young obese (BMI over 30 kg/m^2) adults, nine older (age 50-70 years) normal-weight adults, and eight older obese adults (Table 4.1). Participants were recruited from the university and local community population using advertisements in local newspapers. Exclusion criteria included any self-reported musculoskeletal, neurological, or balance disorders that would affect gait, and greater than 2.3 kg change in body mass over the prior six months. The study was approved by the university Institutional Review Board, and all participants provided written informed consent prior to participation.

Table 4.1: Participant demographics (mean ± standard deviation)

Group	Age (y)	BMI (kg/m^2)
Young Normal-Weight (n=9)	24.0±3.3	22.3± 2.2
Young Obese (n=8)	23.1±3.0	33.4±3.3
Older Normal-Weight (n=9)	60.7±5.9	24.5±1.5
Older Obese (n=8)	59.1±5.6	33.1±3.2

Participants completed a single experimental session with six walking tasks, all of which were performed at a self-selected speed. The first two tasks were performed on a 10 m level walkway and included level walking with and without load carriage in a randomly assigned order. The load was a 6 kg crate held in front of the body with elbows flexed ~90 degrees. The last four tasks were performed on a 2.5 m long 10 degree ramp. The tasks were ramp ascent followed by descent without load carriage, and ramp ascent followed by descent with load carriage. Load carriage tasks were performed in a randomly assigned order. Subjects were told to walk naturally at a comfortable speed with their eyes focused straight ahead, and several practice trials were first completed to allow participants to acclimate to the experimental setup and procedures.

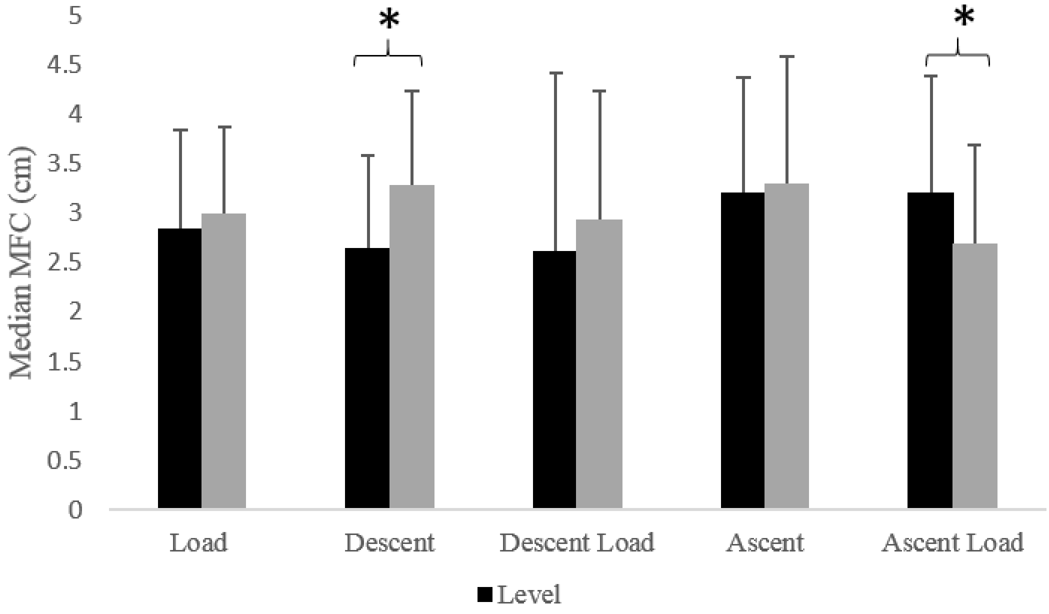
For level walking with and without load carriage, eight trials were performed, and each trial included the swing phase of both the left and right legs. Thus, 16 swing phases were analyzed for each participant at each task. For ramp walking with and without load carriage, four trials were performed per task. Due to the length of the ramp, only the swing phase of the left leg was analyzed for ramp ascent, and only the swing phase of the right leg for ramp descent. Thus, four swing phases for each task on the ramp were analyzed. All participants wore the same brand of athletic shoes in their requested size, and at no point during the experiment were participants told there was a chance they would be perturbed to elicit a fall (i.e., tripped or slipped).

The positions of four reflective markers on each shoe were sampled at 100 Hz using a six-camera motion analysis system (MX-T10, Vicon Motion Systems Inc., L.A, CA), and subsequently low-pass filtered at 5 Hz (8th-order, zero-phase-shift Butterworth filter). MFC during each swing phase was determined using a method adopted from Startzell et al. (Startzell and Cavanagh 1999) and described in detail elsewhere (Garman et al. 2014) . MFC was defined as the lowest of 13 virtual points on the sole of the shoe near the middle of swing. Median MFC and MFC IQR were determined for each participant during each task.

A three way analysis of covariance with planned contrasts was used to evaluate comparisons of interest. Independent variables were task (six tasks), obesity (obese or normal-weight), age (young or older) and all two and three way interactions with both gait speed and body height included as covariates. To address the first hypothesis, contrasts were used to compare median MFC and MFC IQR between level walking without load carriage and the five other tasks. To address the second hypothesis, contrasts were used to compare median MFC and MFC IQR between obesity groups and between age groups within each of the five tasks involving load carriage and/or ramp walking. Only during ramp ascent with load carriage were the effects of obesity (or age) not consistent between age (or obesity) groups. For this task, simple effects were reported. Because ramp ascent calculated MFC exclusively from the left leg, and ramp descent from the right, comparing these tasks with level walking only used data from the right and left leg, respectively. All statistical analyses were performed using JMP 10 (SAS Institute Inc., Cary, NC) with a significance level of $p \leq 0.05$.

4.4 Results

MFC differed from level walking without load carriage during several tasks. Median MFC was 25% higher during ramp descent without load carriage (*p*=0.003), and 16% lower during ramp ascent with load carriage (*p*=0.013). Median MFC was not different during level walking with load carriage (*p*=0.306), ramp descent with load carriage (*p*=0.289), and ramp ascent without load carriage (*p*=0.342l; Figure 4.1). Also compared to level walking without load carriage, MFC IQR was 71% higher during level walking with load carriage (*p*=0.001), 58% higher during ramp descent without load carriage (*p*=0.001), and 53% higher during ramp descent with load carriage (*p*=0.001). MFC IQR was not different during ramp ascent without load carriage (*p*=0.678), and ramp ascent with load carriage (*p*=0.493; Figure 4.1).



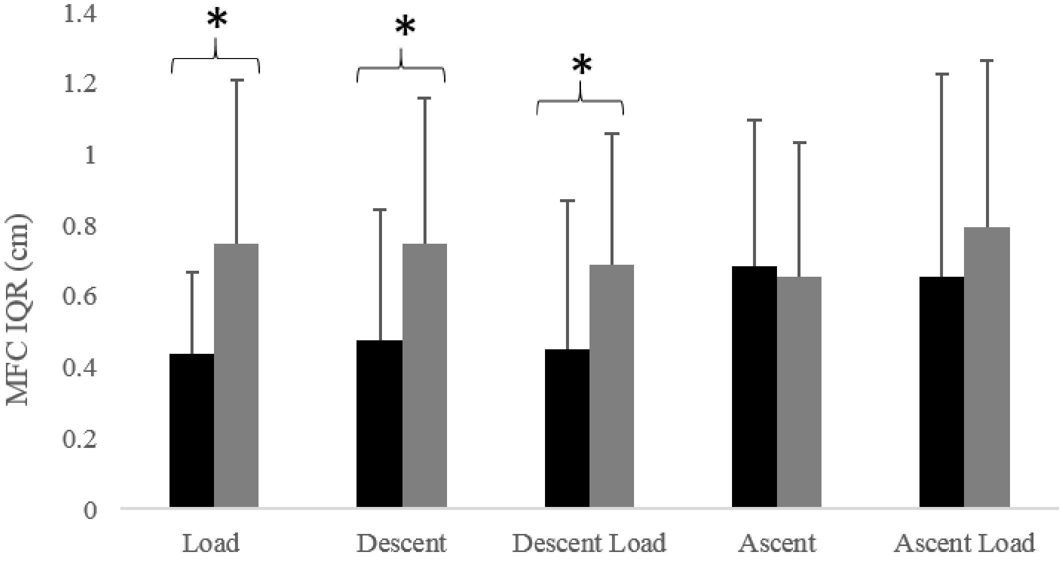
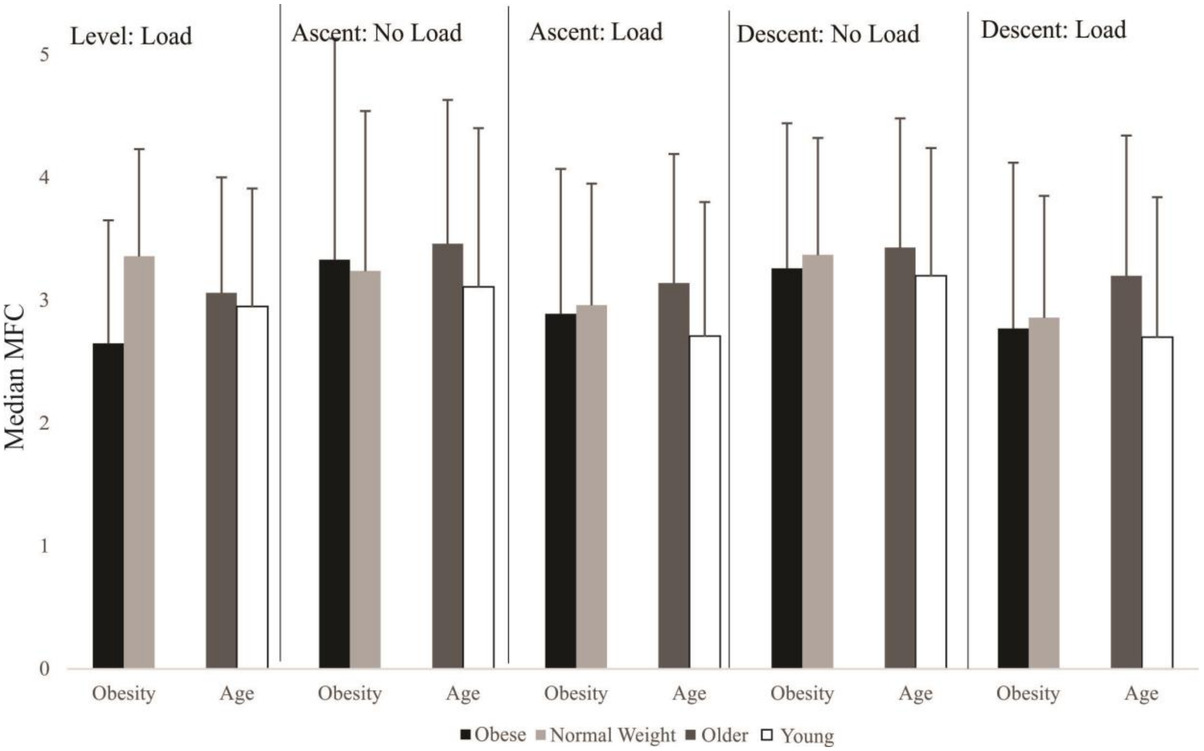


Figure 4.1: The effects of task on median MFC (top) and MFC IQR (bottom). Note all tasks are compared to level walking without load carriage (black bar).

Obesity and age exhibited minimal effects on MFC. During level walking with load carriage, median MFC was not affected by obesity (*p*=0.576) or age (*p*=0.243; Figure 4.1), while MFC IQR was 25% lower among obese compared to normal-weight adults (*p*=0.019) and was not affected by age (*p*=0.876; Figure 4.2)

During ramp descent without load carriage, median MFC was not affected by obesity (*p*=0.803) or age (*p*=0.339; Figure 4.2), while MFC IQR was not affected by obesity (p=0.528) and was 140% higher among older compared to young adults (*p*=0.012). During ramp descent with load carriage, median MFC was not affected by obesity (*p*=0.835) or age (*p*=0.228; Figure 4.2), while MFC IQR was not affected by obesity (*p*=0.087) or age (*p*=0.335).

During ramp ascent without load carriage, median MFC was not affected by obesity (*p*=0.879) or age (*p*=0.574; Figure 4.2), while MFC IQR was not affected by obesity (*p*=0.696) or age (*p*=0.661). During ramp ascent with load carriage, median MFC was not affected by obesity (*p*=0.882) or age (*p*=0.380; Figure 4.2), while MFC IQR had differing effects among age and obesity groups. MFC IQR was 108% higher among normal-weight older compared to normal-weight young adults (*p*=0.0282), and 96% higher among young obese adults compared to young normal-weight adults (*p*=0.048).



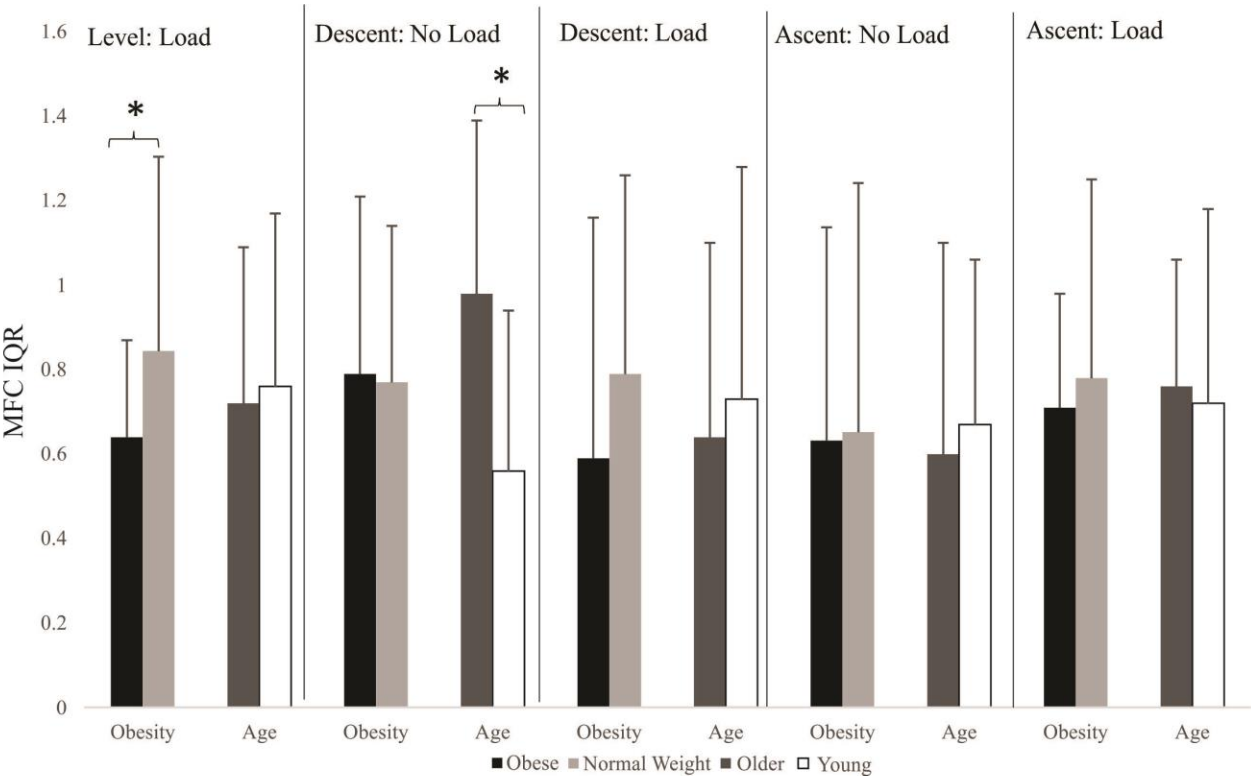


Figure 4.2: The effects of obesity and age on median MFC (top) and MFC IQR (bottom) during occupational tasks.

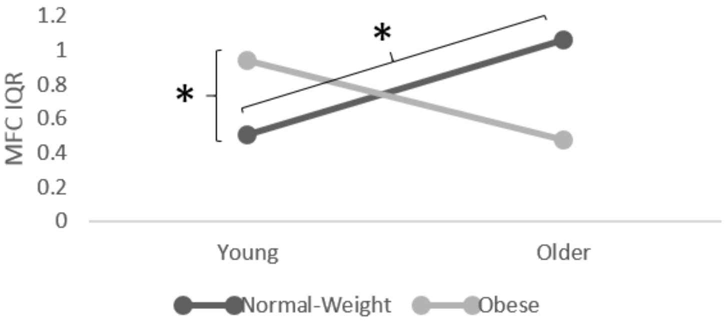


Figure 4.3: Simple effects of obesity and age on MFC IQR during ramp ascent with load carriage * indicates *p*<=0.05.

4.5 Discussion

The primary goal of this study was to investigate the effects of load carriage and ramp walking on the likelihood of tripping. The secondary goal was to investigate the effects of obesity and age on the likelihood of tripping during load carriage and ramp walking. Two hypotheses were posed. First, load carriage, ramp walking and/or ramp walking with load carriage will increase the likelihood of tripping compared to level walking without load carriage. This hypothesis was accepted because ramp ascent with load carriage exhibited lower median MFC, level walking with load carriage exhibited higher MFC IQR, and ramp descent with load carriage exhibited higher MFC IQR. Second, obesity and age will increase the likelihood of tripping during load carriage, ramp walking, and/or ramp walking with load carriage. This hypothesis was accepted because older adults exhibited higher MFC IQR during ramp descent without load carriage, older normal-weight (and young obese) adults exhibited higher MFC IQR compared to young normal-weight (and young obese) adults during ramp ascent with load carriage. These results provide evidence for two general observations. First, load carriage increased the likelihood of tripping during both level and ramp walking. Second, obesity and age increased the likelihood of tripping during selected combinations of load carriage and/or ramp walking. No general observations with respect to ramp walking could be made due to either no effects on MFC (no MFC differences between ramp ascent without load carriage and level walking without load carriage) or ambiguous effects on MFC (both median MFC and MFC IQR were higher during ramp descent without load carriage compared to level walking without load carriage). These results support the need for further study to quantify the increased likelihood of tripping associated with load carriage, obesity, and aging, and to explore strategies to control the frequency of these accidents.

With respect to the effect of task on MFC measures, the 25% increase in median MFC during ramp descent without load carriage was consistent with the 33% increase reported by Khandoker *et al*. (2010), but lower than the 100% increase reported by Thies *et al*. (2011). The effect of ramp ascent without load carriage has been inconsistent between studies. Studies have reported increases in median MFC (Prentice et al. 2004, Thies et al. 2011) and decreases in median MFC (Khandoker et al. 2010), while the current study was unable to find any effect. Only two studies to our knowledge investigated the effects of ramp ascent and descent without load carriage on MFC IQR, and neither were able to find an effect (Khandoker et al. 2010, Thies et al. 2011). Contrary to these finding we found a 58% increase in MFC IQR during ramp descent without load carriage. When adding load carriage to level walking, no studies, including the current study, have reported a change in median MFC (Rietdyk et al. 2005, Schulz et al. 2010). However, we did find a 71% increase in MFC IQR when adding load carriage to level walking. It is possible that some of the differences in results between studies could have resulted from differences in study protocols. Slope variations were abundant in studies examining ramp walking. For example, slopes included 3 degrees (Khandoker et al. 2010), 4.7 degrees (Thies et al. 2011), 12 degrees (Prentice et al. 2004), and 10 degrees (our study). Mass variations also existed between studies investigating load carriage. Mass's included 5% of subject body weight (Rietdyk et al. 2005), 9 kg (Schulz et al. 2010) and 6 kg (our study). Additionally, the number of participants in the current study was an average of 10 participants larger than the other studies reported here. This larger sample size may have facilitated in the detection of some of these effects, such as the increase in MFC IQR during load carriage.

For ramp descent without load carriage, median MFC and MFC IQR increased concurrently leading to an ambiguous indication of likelihood of tripping. The increase in median MFC is most likely due to the descending slope of the ground, while the variability may be attributed to increased task difficulty compared to level walking. Ramp descent would be a particularly dangerous time to experience a trip as tripping induces a forward rotation of the body which is worsened by the descending slope of the ramp. As such, further analysis should be completed to more fully understand the effects of ramp descent on likelihood of tripping so that safety measures can be explored.

To the best of our knowledge, this was the first study to investigate the effects of ramp walking with load carriage on MFC. Ramp walking and load carriage are hypothesized to effect MFC measures through two different mechanisms. Compared to level walking, ramp walking is a difficult task in that joint moments are prolonged and continuous postural adjustment are necessary for proper ambulation of the slope. Anterior load carriage increases inertial load and obstructs the view of the foot floor interface impairing visual feedback. Both tasks are thought to increase gait variability and hence MFC IQR. One may speculate simultaneous ramp walking and load carriage would cause a considerable increase in MFC IQR. Our results showed ramp descent with load carriage increased MFC IQR, suggesting an increase in the likelihood of tripping. However, ramp ascent with load carriage did not increase MFC IQR, but did decrease median MFC, still suggesting an increase in the likelihood of tripping. Median MFC and MFC IQR have been reported to be positively correlated (Begg et al. 2007, Garman et al. 2014). Intuitively, as MFC is decreased there is less room for variations in MFC values, hence MFC IQR is concurrently reduced. As such, the lower median MFC seen during ramp ascent with load carriage may have contributed to the unexpected lack of increase in MFC IQR. Regardless, both ramp ascent and descent with load carriage should be executed cautiously as both appear to increase the likelihood of tripping.

To the best of our knowledge, no studies have investigated the effects of obesity on MFC during ramp walking and load carriage. Only one study has investigated the effects of age on MFC during ramp walking (Khandoker et al. 2010). This prior study reported no effects of age on median MFC and MFC IQR during both ramp ascent and ramp descent (Khandoker et al. 2010). However, the current study identified an increase in MFC IQR among older adults during ramp descent. A noteworthy difference in experimental setup may have contributed to this difference in that Khandoker *et al* (2010) used a ramp slope of 3 degrees whereas the current study used a slope of 10 degrees. Perhaps the larger ramp angle elicited larger changes in MFC IQR.

Ramp walking in conjunction with load carriage revealed additional differences between young and older adults in addition to differences between obese and normal-weight adults. Among normal-weight adults, older adults displayed a higher MFC IQR during ramp ascent with load carriage (Figure 4.2). Ramp walking is speculated to be a more difficult task for individuals, such as older adults, with strength and musculoskeletal control limitations (Redfern and DiPasquale 1997). During ramp ascent alone, this difficulty may not be sufficient to produce noticeable changes in gait variability measures. Adding a task such as load carriage that causes visual occlusion of the foot floor interface and increases inertial load likely facilitated in the detection of a significant increase in gait variability, more specifically MFC IQR, among older adults. The same may be speculated for the higher MFC IQR in young obese adults (Figure 4.3). Obese adults have been reported to have a decrease in relative strength and power (Hulens et al. 2001, Maffiuletti et al. 2007). Additionally, the difficulty of ramp ascent may be intensified among obese as joint moments may be even higher due to the added body weight. While joint moments were not investigated in the current study future analysis may be performed to examine just how much obesity influences these variables during ramp negotiation.

Three limitations to this work warrant mention. First, the method used to calculate MFC assumed that the shoe is a rigid body. While this is clearly not true, it was considered reasonable during swing when no external forces were applied to the shoe. Second, as with any cross sectional study, other differences between groups besides the characteristics reported here could have contributed to the results. Third, a direct quantitative relationship between median MFC/MFC IQR and trip occurrence has not been established, so the actual increase in likelihood of tripping elicited by ramp walking and/or load carriage is unknown.

4.6 Conclusion

Load carriage increased the likelihood of tripping during both level and ramp walking. Additionally, advanced age increased likelihood of tripping during ramp descent and both obesity and advanced age increases likelihood of tripping during ramp ascent with load carriage. These results suggest that the increased rate of falling during load carriage reported elsewhere may be due in part to an increased risk of tripping. Moreover, the increased rate of falling among obese and older adult workers reported elsewhere may be due in part to an increased risk of tripping during occupationally relevant tasks such as ramp walking and load carriage.

4.7 Acknowledgements

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4.8 References

Ambrose, A. F., G. Paul and J. M. Hausdorff (2013). "Risk factors for falls among older adults: A review of the literature." Maturitas **75**(1): 51-61.

Barrett, R. S., P. M. Mills and R. K. Begg (2010). "A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking." Gait & Posture **32**(4): 429-35.

Begg, R., R. Best, L. Dell'Oro and S. Taylor (2007). "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls." Gait & Posture **25**(2): 191-98.

Cohen, H. H. and D. M. Compton (1982). "Fall accident patterns: Characterization of most frequent work surface-related injuries." Professional Saftey **6**(16-22).

Courtney, T. K. and B. S. Webster (2001). "Antecedent factors and disabling occupational morbidity-insights from the new bls data." American Industrial Hygiene Association **62**: 622-32.

CPWR (2007). "The construction chart book by: The center for construction research and training (4th ed.): With support from the national insistue for occupational safety and health grant number oh008307."

Garman, C. R., S. L. Arena, M. A. Nussbaum, C. T. Franck and M. L. Madigan (2014). "Minimum foot clerance during overground walking is lower among females but not affected by obesity." In review (Journal of Electromyography and Kinesiology).

Goodpaster, B. H., S. W. Park, T. B. Harris, S. B. Kritchevsky, M. Nevitt, A. V. Schwartz, E. M. Simonsick, F. A. Tylavsky, M. Visser and A. B. Newman (2006). "The loss of skeletal muscle strength, mass, and quality in older adults: The health, aging and body composition study." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **61**(10): 1059-64.

Hertz, R. (2000). "Obesity in the united states workforce: Findings from the national health and nutrition examination surveys" Retrieved May 16, 2014, from http://www.pfizer.com/files/products/Obesity_in_the_United_States_Workforce.pdf.

Hulens, M., G. Vansant, R. Lysens, A. Claessens, E. Muls and S. Brumagne (2001). "Study of differences in peripheral muscle strength of lean versus obese women: An allometric approach." International Journal of Obesity Related Metabolic Disorder **25**(5): 676-81

Kemmlert, K. and L. Lundholm (2001). "Slips, trips and falls in different work groups — with reference to age and from a preventive perspective." Applied Ergonomics **32**(2): 149-53.

Khandoker, A. H., K. Lynch, C. K. Karmakar and R. K. Begg (2010). "Toe clearance and velocity profiles of young and elderly during walking on sloped surfaces." Journal of NeuroEngineering and Rehabilitation **7**.

Lafortuna, C. L., N. A. Maffiuletti, F. Agosti and S. A. (2005). "Gender variations of body composition, muscle strength and power output in morbid obesity." International Journal of Obesity **29**(7): 833-41.

Layne, L. and K. Pollack (2004). "Nonfatal occupational injuries from slips, trips, and falls among older workers treated in hospital emergency departments, united states 1998." American Journal of industrial medicine **46**(1): 32-41.

Leamon, T. B. and P. L. Murphy (2010). "Occupational slips and falls: More than a trivial problem." Ergonomics **38**(3): 487-98.

Lipscomb, H. J., J. E. Glazner, J. Bondy, K. Guarini and D. Lezotte (2006). "Injuries from slips and trips in construction." Applied Ergonomics **37**(3): 267-74.

Luckhaupt, S. E., M. A. Cohen, J. Li and G. M. Calvert (2014). "Prevalence of obesity among u.S workers and associations with occupational factors

" American Jounral of Preventive Medicine **46**(3): 237-48.

Maffiuletti, N. A., M. Jubeau, U. Munzinger, M. Bizzini, F. Agosti, A. De Col, C. L. Lafortuna and A. Sartorio (2007). "Differences in quadriceps muscle strength and fatigue between lean and obese subjects." European Jounral of Applied Physiology **101**(1): 51-9.

Mills, P. M., R. S. Barrett and S. Morrison (2008). "Toe clearance variability during walking in young and elderly men." Gait & Posture **28**(1): 101-07.

Niechwiej-Szwedo, E., E. L. Inness, J. A. Howe, S. Jaglal, W. E. McIlroy and M. C. Verrier (2007). "Changes in gait variability during different challenges to mobility in patients with traumatic brain injury." Gait & Posture **25**(1): 70-77.

Prentice, S. D., E. N. Hasler, J. J. Groves and J. S. Frank (2004). "Locomotor adaptations for changes in the slope of the walking surface." Gait & posture **20**(3): 255-65.

Redfern, M. and J. DiPasquale (1997). "Biomechanics of descending ramps." Gait & Posture **6**(2): 119-25.

Rhea, C. K. and S. Rietdyk (2007). "Visual exteroceptive information provided during obstacle crossing did not modify the lower limb trajectory." Neuroscience Letters **418**(1): 60-65.

Rietdyk, S., J. D. McGlothlin, J. L. Williams and A. T. Baria (2005). "Proactive stability control while carrying loads and negotiating an elevated surface." Experimental Brain Research **165**: 44-53.

Rosenblatt, N. J. and M. D. Grabiner (2012). "Relationship between obesity and falls by middle-aged and older women." Archives of Physical Medicine and Rehabilitation **93**(4): 718-22.

Saftey, L. M. R. I. f. (2012). "2013 liberty mutual workplace safety index." Retrieved May 25, 2014, from www.libertymutualgroup.com/researchinstitute.

Schulz, B. W., J. D. Lloyd and W. E. Lee Iii (2010). "The effects of everyday concurrent tasks on overground minimum toe clearance and gait parameters." Gait & Posture **32**(1): 18-22.

Shultz, S. P., M. R. Sitler, R. T. Tierney, H. J. Hillstrom and J. Song (2009). "Effects of pediatric obesity on joint kinematics and kinetics during 2 walking cadences." Archives of physical medicine and rehabilitation **90**(12): 2146-54.

Startzell, J. K. and P. R. Cavanagh (1999). "A three-dimensional approach to the calculation of foot clearance during locomotion." Human Movement Science **18**(5): 603-11.

Swaen, G., J. J. Burns, K. M. Collins, J. F. Bodner, B. A. Dizor and E. M. Bonner (2014). "Slips, trips and falls at a chemical manufacturing company." Occupational Medicine Advance Access

Thies, S. B., R. K. Jones, L. P. J. Kenney, D. Howard and R. Baker (2011). "Effects of ramp negotiation, paving type and shoe sole geometry on toe clearance in young adults." Journal of Biomechanics **44**(15): 2679-84.

U.S. Bureau of Labor Statistics, U. S. D. o. L. (2009). "2012 census of fatal occupational injuries." Retrieved May 19, 2014, from http://www.bls.gov/iif/oshcfoi1.htm.

Winter, D. A. (1992). "Foot trajectory in human gait: A precise and multifactorial motor control task." Physical Therapy **72**(1): 45-53.

Chapter 5: A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height

5.1: Abstract

Tripping is a common mechanism for inducing falls. The purpose of this study was to present a method that determines the probability of tripping over an unseen obstacle while avoiding the ambiguous situation wherein median minimum foot clearance (MFC) and MFC interquartile range concurrently increase or decrease, and determines how the probability of tripping varies with potential obstacle height. The method was used to investigate the effects of age, obesity, gender, and gait speed on the probability of tripping. MFC was measured while 80 participants walked along a 10- meter walkway at self-selected and hurried gait speeds. The method was able to characterize the probability of tripping as a function of obstacle height, and identify effects of age, obesity, gender, and gait speed. More specifically, the probability of tripping was lower among older adults, higher among obese adults, higher among females, and higher at the slower self-selected speed. Many of these results were not found, or clear, from the more common approach on characterizing likelihood of tripping based on MFC measures of central tendency and variability

5.2 Introduction

Fall-related injuries among older adults are a major public health problem due to their high medical costs and negative impact on quality of life (Bruce et al. 1992). Tripping accounts for 35-53% of these falls (Berg et al. 1997, Blake et al. 1998). The most common measure for characterizing the probability of tripping while walking is the minimum foot clearance (MFC) during swing. A decrease in the central tendency (i.e. mean/median) of MFC, or an increase in

MFC variability, are both associated with an increased probability of tripping (Winter 1992, Begg et al. 2007, Mills et al. 2008). These indirect measures of probability of tripping, however, can lead to ambiguous results when both increase or decrease simultaneously. For example, Nagano *et al.* (2011) reported higher median MFC and MFC interquartile range (IQR, a measure of MFC variability) during overground walking compared to treadmill walking (Nagano et al. 2011), and Rossi *et al.* (2013) reported higher median MFC and MFC IQR in the non-dominant leg and at faster gait speeds (Rossi et al. 2013). Median MFC and MFC IQR are also positively correlated (Begg et al. 2007), indicating concurrent increases or decreases in both are to be expected.

The purpose of this study was to present a method that determines the probability of tripping over an unseen obstacle while avoiding the ambiguous situation wherein median MFC and MFC IQR concurrently increase or decrease, and determines how the probability of tripping varies with potential obstacle height. The method was used to investigate the effects of age, obesity, gender, and gait speed on the probability of tripping. These factors were investigated based upon reports of elevated risks of falling and fall-related injuries among adults over the age of 65 (Bruce et al. 1992, Kannus et al. 1999), individuals who are obese (Fjeldstad et al. 2008, Himes and Reynolds 2012, Patino et al. 2010), females (Stevens 2005, Ambrose et al. 2013), and changes in risk of tripping with gait speed (Schulz 2011, Rossi et al. 2013).

5.3 Methods

Eighty participants completed the study including four gender-balanced groups comprised of 20 participants each (Table 1). None of the participants self-reported a change in body mass of >2.3

kg over the six months prior to testing, or any musculoskeletal, neurological, or balance disorders that would affect gait. The study was approved by the university Institutional Review Board, and all participants provided written informed consent prior to participation.

Participants walked along a 10-meter level walkway at a self-selected speed (always performed first) and a hurried speed of 1.9 m/s. Eight trials at each speed were completed, and data obtained from each trial included the swing phase of both the dominant and non-dominant leg. Thus, 16 swing phases were analyzed from each participant at each speed. The positions of three reflective markers attached to the shoe were sampled at 100 Hz using a Vicon MX motion analysis system (Vicon Motion Systems Inc., LA, CA). Multiple virtual points on the sole of the shoe were tracked using a method described elsewhere (Startzell and Cavanagh 1999), and MFC was defined as the lowest of all points near mid-swing in a given swing phase.

Table 5.1: Participant demographics (mean ± standard deviation). Note: NW = normal-weight group, OB = obese group, F = female, M = male

	Young		Older	
	NW	OB	NW	OB
Sample Size	F: (n=10) M: (n=10)	F: (n=10) M: (n=10)	F: (n=10) M: (n=10)	F: (n=10) M: (n=10)
Age (years)	F: 24.4 ± 3.4 M: 23.8 ± 3.2	F: 24.8 ± 2.8 M: 21.9 ± 2.5	F: 66.8 ± 4.9 M: 65.8 ± 4.6	F: 65.6 ± 5.5 M: 74.3 ± 6.1
BMI (kg/m^2)	F: 23.1 ± 2.2 M: 21.2 ± 1.7	F: 34.0 ± 3.5 M: 33.2 ± 3.1	F: 23.8 ± 2.0 M: 24.5 ± 1.4	F: 33.1 ± 2.0 M: 31.5 ± 1.7

MFC values were used to create trip probability curves that indicated how the probability of tripping varied as a function of height of a potential tripping obstacle (Figure 1). For potential tripping obstacle heights ranging from 0 - 7 cm, in increments of 2 mm, each experimental MFC value was dichotomized as either a trip (if the potential obstacle height was greater than MFC) or a non-trip (if the potential obstacle height was equal to or less than MFC). The percentages of trips at each obstacle height were then computed, serving as an estimate of the probability of tripping.

A statistical bootstrapping technique (Duhamel et al. 2004), was then used at each potential obstacle height to determine whether the probability of tripping differed by age group, obesity group, gender, or gait speed condition. The first step in this technique was to randomly reassign group labels to each of the 16 MFC values from each participant (e.g. young or older when investigating age effects). A probability curve was then created for each group, and the difference in trip probability between groups was calculated at each potential obstacle height. This process was performed 100,000 times to obtain a distribution of differences at each potential obstacle height that would occur if group assignment was random. This distribution acted as the sampling distribution of differences under the null hypothesis that the groups had equal trip probabilities.

The second step in this technique was to determine whether the actual observed difference in probability of tripping between groups was statistically significant. The actual observed difference in probability of tripping between groups was defined as the absolute value of the difference between the group percentages at a potential obstacle height. Because each bootstrapping analysis involved 36 comparisons between groups (0-7 cm obstacles heights in increments of 2 mm), the significance level was 0.05/36, or α=0.0014, to avoid consequences of type I errors. As such, if the actual difference in probability of tripping was in the outer 0.14% of the distribution, then the difference in trip probability between groups was considered statistically significant. Alternatively, the percentage of the distribution of differences outside of the actual observed difference yielded a bootstrap *p*-value. This second step was performed for all potential obstacle heights, and between all participant groups of interest, to determine the specific heights at which the probability of tripping differed between groups.

Group differences identified from this statistical bootstrapping technique were compared with group differences identified using the traditional measures of median MFC and MFC IQR. Group differences in median MFC and MFC IQR were determined using a four-way, mixed-factor analyses of covariance (ANCOVA) with planned contrasts. Independent variables in the ANCOVAs were age, obesity, and gender, and gait speed was the covariate. Analyses were performed using JMP v7 (Cary, North Carolina, USA).

5.4 Results

Age-related differences in the probability of tripping were not consistent between the bootstrapping technique and the ANCOVA analysis. Among normal-weight adults (Figure 1a), the probability of tripping was lower among older adults across a range of obstacle heights (2.0-4.6 cm), while no age effects were found for either median MFC or MFC IQR. Among obese adults (Figure 1b), the probability of tripping was also lower among older adults, but across a smaller range of obstacle heights (1.2-2.4 cm), while again there were no age effects for either median MFC or MFC IQR.

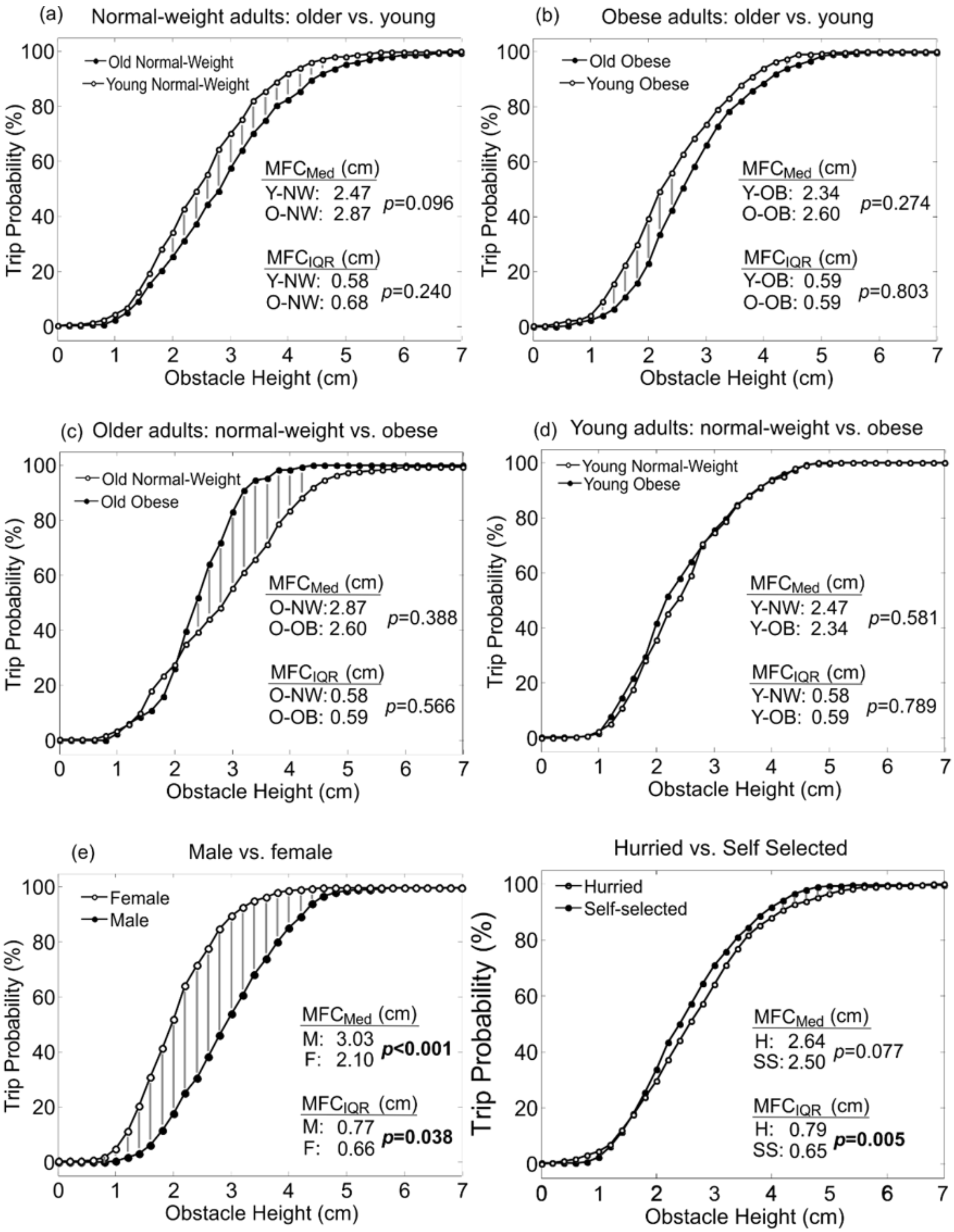

Figure 5.1: Trip probability curves and median/IQR MFC separated by age group, obesity group, gender and speed. Differences in probability of tripping between groups (*p*<0.05) are indicated by a solid vertical line, and differences in median/IQR MFC are indicated by bold.

Obesity-related differences in the probability of tripping were also not consistent between the bootstrapping technique and the ANCOVA analysis. Among older adults (Figure 1c), the probability of tripping was significantly higher among obese adults across a range of obstacle heights (2.4-4.2 cm), while there were no obesity effects on median MFC or MFC IQR. Among young adults (Figure 1d), there were no significant effects of obesity on the probability of tripping, nor on median MFC or MFC IQR. With respect to gender (Figure 1e), the probability of tripping was higher among females across a range of obstacle heights (0.8-4.4 cm), while both median MFC and MFC IQR were lower among females. With respect to speed (Figure 1f), the probability of tripping was lower for the faster hurried speed across a narrow range of obstacle heights (4.2-5 cm), while both median MFC (approached significance) and MFC IQR were higher at the faster hurried speed.

5.5 Discussion

While prior work has employed median MFC and MFC IQR as indirect measures of likelihood of tripping, the method presented here directly determines the probability of tripping as a function of obstacle height, and uses a statistical bootstrapping technique to compare this probability between groups of interest. This technique identified effects of age and obesity that were not identified from the more traditional approach using ANOVA. This new technique also identified effects of gender and gait speed, and helped clarify ambiguous results from the ANCOVA analysis with respect to probability of tripping (e.g. when both median MFC and MFC IQR were higher among males compared to females).

Three limitations to the method presented here warrant mentioning. First, this method, along with ANOVA using median/mean MFC and MFC IQR, focuses on foot clearance at the instant that MFC occurs, even though a trip could occur at other instances during the swing phase. Second, unlike an ANOVA based upon median/mean MFC and/or MFC IQR, the current method cannot incorporate measures of covariance, or statistically control for the effects of other variables, when evaluating an independent variable of interest. Third, this method, along with most other investigations of MFC, assumes individuals will not see or react to an obstacle in their path. While this may be true for smaller obstacles, this is less likely for larger obstacles.

The method presented here may be helpful in ensuring that safety guidelines are inclusive and protective for diverse populations. For instance, The Americans with Disabilities Act (ADA) stipulates that abrupt changes in height of a walkway greater than 6 mm require edge treatment to account for individuals in wheelchairs and individuals whose foot is impeded during the swing phase of gait (Cohen and Abele 2007). The results in Figure 1c indicate that trip probability does not differ between normal-weight and obese older adults unless obstacle height exceed 2.4 cm, suggesting that the 6 mm standard of the ADA is equally protective for both of these populations.

A statistical modeling technique reported by (Best and Begg 2008) also characterizes the probability of tripping over a range of obstacle heights. While this modeling technique helps recognize the features of the distribution of MFC data (i.e skewness and kurtosis), the method reported here may provide a pragmatic alternative for characterizing the probability of tripping. Of note, though, is that trip probabilities obtained from the two methods differed substantially.

For an obstacle height of 1 cm, Best and Begg (2008) reported a trip probability of 50% (Best and Begg 2008) whereas the current method yielded a probability of less than 5% (depending upon the specific group of interest). This difference may be due to methodological differences between the two studies including overground vs treadmill walking, walking speeds, number of participants, and methods used to estimate MFC.

5.6 Conclusion

The method presented here identified differences in probability of tripping that provided both novel and complementary insight to the literature. Regarding obesity, no studies to our knowledge have reported effects of obesity on median/IQR MFC. The higher probability of tripping among obese individuals found here (albeit only among older adults) may help to explain the higher fall rates among individuals who are obese (Fjeldstad et al. 2008). Regarding gender, lower median MFC among females reported by Rossi et al. (2013) is consistent with the median MFC results presented here. However, the concurrently lower MFC IQR among females also reported here obscures the net effect of these differences on probability of tripping. The current method provides clear and direct biomechanical evidence that the probability of tripping is higher among females. Interestingly, these results appear to align with those by Berg et al., who in a one-year prospective survey study of adults aged 60-88, found that falls among females most often occurred due to tripping whereas falls among males most often occurred due to slipping (Berg et al. 1997). The present method also has the advantage of identifying the specific obstacle heights at which group differences exist, which may be helpful for various trip and fall prevention strategies.

5.7 Acknowledgments

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5.8 References

Ambrose, A. F., G. Paul and J. M. Hausdorff (2013). "Risk factors for falls among older adults: A review of the literature." Maturitas **75**(1): 51-61.

Begg, R., R. Best, L. Dell'Oro and S. Taylor (2007). "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls." Gait & Posture **25**(2): 191-98.

Berg, W. R., H. M. Alessio, E. M. Mills and C. Tong (1997). "Circumstances and consequences of falls in independent community dwelling older adults." Age Ageing **26**(4): 261-68.

Best, R. and R. Begg (2008). "A method for calculating the probability of tripping while walking." Journal of Biomechanics **41**(5): 1147-51.

Blake, A. J., K. Morgan, M. J. Bendall, H. Dallosso, S. B. J. Ebrahim, T. H. D. Arie, P. H. Fentem and E. J. Bassey (1998). "Falls by elderly people at home - prevalence and associated factors." Age Ageing **17**(6): 365-72.

Bruce, A. H., R. P. Fredenck and W. E. Marsha (1992). "The cost and frequency of hospitalization for fall-related injuries in older adults." American Journal of Public Health **82**(7): 1020-30.

Cohen, H. H. and J. R. Abele (2007). Slips, trips, missteps, and their consequences, Lawyers & Judges Publishing Company.

Duhamel, A., J. L. Bourriez, P. Devos, P. Krystkowiak, A. Destee, P. Derambure and L. Defebvre (2004). "Statistical tools for clinical gait analysis." Gait Posture **20**(2): 204-12.

Fjeldstad, C., A. S. Fjeldstad and L. S. Acree (2008). "The influence of obesity on falls and quality of life." Dynamic Medicine **7**(4).

Himes, C. L. and S. L. Reynolds (2012). "Effect of obesity on falls, injury and disability." Journal of the American Geriatrics Society **60**(1): 124-29.

Kannus, P., J. Parkkari, S. Koskinene, S. Niemi, M. Palvanen, M. Järvinen and I. Vuori (1999). "Fall-induced injuries and deaths among older adults." Jounral of the American Medical Association **281**(20): 1895-99.

Mills, P. M., R. S. Barrett and S. Morrison (2008). "Toe clearance variability during walking in young and elderly men." Gait & Posture **28**(1): 101-07.

Nagano, H., R. K. Begg, W. A. Sparrow and S. Taylor (2011). "Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking." Clinical Biomechanics **26**(9): 962-68.

Patino, C. M., R. Mckean-Cowdin, S. Azen, J. C. Allison, F. Choudhury and R. Varma (2010). "Central and peripheral visual impairment and the risk of falls and falls with injury." Ophthalmology. **117**(2): 199-206.

Rossi, C. M., S. Matrangola, M. A. Nussbaum and M. L. Madigan (2013). Effects of age and obesity on risk of tripping during level walking. Annual Meeting for the American Society of Biomechanics,. Omaha, Nebraska.

Schulz, B. W. (2011). "Minimum toe clearance adaptations to floor surface irregularity and gait speed." Journal of Biomechanics **44**(7): 1277-84.

Startzell, J. K. and P. R. Cavanagh (1999). "A three-dimensional approach to the calculation of foot clearance during locomotion." Human Movement Science **18**(5): 603-11.

Stevens, J. A. (2005). "Gender differences for non-fatal unnintentional fall related injuries among older adults " Injury Prevention **11**: 115-19.

Winter, D. A. (1992). "Foot trajectory in human gait: A precise and multifactorial motor control task." Physical Therapy **72**(1): 45-53.

Chapter 6: Obesity and advanced age increase fall rate following a laboratory-induced trip

6.1 Abstract

Obese and older adults are reported to fall more frequently than their normal-weight and young counterparts. To help identify potential mechanisms of these falls, this study investigated the effects of obesity and age on balance recovery following a laboratory-induced trip. Thirty-nine participants (10 young normal-weight, 11 young obese, 8 older normal-weight, and 10 older obese adults) performed 10 gait trials on a 10 m walkway at a controlled gait speed (1.4-1.6 m/s). During the 11th trial, a 7 cm high obstacle was raised to elicit a trip near mid-swing. Fall rate was 52% among obese adults and 22% among normal-weight adults. Peak trunk angle was 13 degrees higher among obese adults compared to normal-weight adults and peak trunk angular velocity was 216 degrees/s higher among obese older adults compared to normal-weight older adults, and 245 degrees/s higher among obese older adults compared to obese young adults. Obesity did not influence recovery stepping strategy or characteristics. Main effects of age and gender were also revealed in that older adults and females had higher fall rates, higher peak trunk angles and angular velocities and were more likely to use lowering strategies. The study suggests obese, older and female adults have an impaired ability to recovery balance following a trip perturbation which may be due in part to altered trunk kinematics and stepping strategies.

6.2 Introduction

The societal and economic impact of fall-related injuries in the United States has the capacity to escalate as a result of two major demographic trends. First, the prevalence of obesity in the United States has increased dramatically over the past decades from 13% in the 1960’s (Wang and

Beydoun 2007) to 35% in 2011-2012 (Ogden et al. 2014). Second, the number of adults over the age of 65 is projected to more than double from 2006 to 2050 (WHO 2007). These trends are problematic because obesity and advanced age are both associated with higher rates of falling (WHO 2007, Fjeldstad et al. 2008) and sustaining fall-related injuries (Finkelstein et al. 2007, WHO 2007).

Tripping accounts for an estimated 35-53% of falls among older adults aged 65 and above (Berg et al. 1997, Blake et al. 1998). As such, balance recovery following a trip, or trip recovery, has been studied extensively in the older adult population (Pavol et al. 1999, Pavol et al. 1999, Pavol et al. 2002, Van den Bogert et al. 2002, Pijnappels et al. 2004, Pijnappels et al. 2004, Pijnappels et al. 2005, Pijnappels et al. 2008, Pijnappels et al. 2008). Older adult have been shown to have a higher fall rate than young adults after a laboratory-induced trip (Pijnappels et al. 2008), with likely contributing factors of decreased strength in the lower limbs, slower rate of moment generation (Pijnappels et al. 2004), and increased response time (Van den Bogert et al. 2002, Pijnappels et al. 2004, Pijnappels et al. 2004).

The effect of obesity on trip recovery has received little attention. Rosenblatt and Grabiner (2012) showed that the fall rate after a laboratory-induced trip was almost twice as high among obese female adults (46%) compared to non-obese female adults (25%), although this difference did not reach statistical significance. These investigators also reported the majority of obese fallers were not able to initiate or complete a recovery step, suggesting an impaired stepping response as a contributor to the higher fall rate. Obese adults have lower strength and power relative to body mass (Hulens et al. 2001, Lafortuna et al. 2005, Maffiuletti et al. 2007). Additionally, the body mass distribution among obese adults can cause an anterior shift in the whole body center of mass (COM) location, making balance more challenging during recovery from a forward loss of balance as is common after tripping (Corbeil et al. 2001). Decreased relative strength in conjunction with the anterior shift of the COM would seem to make trip recovery more challenging, and could account for the higher trip and fall rate reported by Rosenblatt and Grabiner (2012), and the overall higher fall rate among individuals who are obese (Fjeldstad et al. 2008).

Successful trip recovery requires arresting the forward angular momentum of the trunk (Grabiner et al. 1996, Pavol et al. 2001, Pijnappels et al. 2004). For example, Pavol et al. (2001) reported peak trunk angle was 54.7 degrees lower and the angular velocity of the head arm torso segment was 83.5 degrees/second lower among successful recoveries compared to failed recoveries (Pavol et al. 2001). A common strategy to arrest this momentum is to employ a stepping strategy to extend the base of support anteriorly, and provide vertical and posterior ground reaction forces after stepping (Grabiner et al. 1996, Madigan and Lloyd 2005). As such, stepping characteristics and trunk kinematics are critically important during trip recovery. Two general stepping strategies have been documented during trip recovery. Early swing perturbations typically elicit an elevating strategy in which the swing limb that contacts the tripping obstacle is immediately lifted over the obstacle in an attempt to complete a recovery step over the obstacle (Eng et al. 1994, Schillings et al. 2000, Pijnappels et al. 2004). Late swing perturbations typically elicit a lowering strategy in which the swing limb that contacts the tripping obstacle is immediately lowered to the ground on the near side of the obstacle, then a step over the obstacle is attempted with the contralateral limb

(Eng et al. 1994). Mid-swing perturbations can elicit both elevating and lowering strategies (Schillings et al. 2000).

The purpose of this study was to investigate the effects of obesity and age on trip recovery. Dependent variables included measures of fall rate, stepping strategy and characteristics, and trunk kinematics. We hypothesized 1) obese adults would fall at a higher rate compared to normal-weight adults 2) obese adults would exhibit less favorable stepping strategy/characteristics and/or trunk kinematics compared to normal-weight adults, and 3) the adverse effects of obesity would be magnified among older adults. Although not our main focus, we also investigated the effects of age and gender on the same dependent variables, and explored differences between successful and failed recoveries. Results from this study can help identify the reasons behind the elevated fall rate among obese individuals, identify other factors contributing to falls from tripping, and help identify modifiable risk factors for targeted interventions.

6.3 Methods

Thirty-nine participants completed the study including 10 young (age 18-30 years) normal-weight (body mass index, or BMI, of 18-24.9 kg/m^2) adults, 11 young obese adults (BMI over 30 kg/m^2), 8 older (age 50-70 years) normal-weight adults, and 10 older obese adults (Table 6.1). Participants were recruited from the university and local community population with exclusion criteria including any self-reported musculoskeletal, neurological, or balance disorders that would affect gait, and a greater than 2.3 kg change in body mass over the prior six months.

Participants over the age of 65 were required to have a dual-energy x-ray absorptiometry scan to insure the bone mineral density of the femoral neck was greater than 0.65 g/cm^2. The study was approved by the university Institutional Review Board, and all participants provided written informed consent prior to participation.

Table 6.1: Participant demographics (mean ± standard deviation)

	Young		Older	
	NW	OB	NW	OB
Sample Size	F: (n=6) M: (n=4)	F: (n=5) M: (n=6)	F: (n=4) M: (n=4)	F: (n=5) M: (n=5)
Age (years)	F: 27.3 ± 2.3 M: 23.5 ± 2.5	F: 24.8 ± 2.8 M: 21.9 ± 2.5	F: 65.0 ± 2.9 M: 66.2 ± 4.6	F: 67.8 ± 4.7 M: 64.6 ± 4.1
BMI (kg/m^2)	F: 22.2 ± 1.7 M: 23.9 ± 1.7	F: 34.5 ± 4.5 M: 33.8 ± 3.1	F: 22.6 ± 2.3 M: 24.5 ± 1.4	F: 33.8 ± .95 M: 31.8 ± 1.7

All testing was performed in a single experimental session. Participants were given a verbal overview of the protocol, and informed there was a chance they would be either tripped or slipped to elicit a fall. Participants then donned standardized athletic clothes, shoes, and a full body safety harness to prevent impact of the knees or hands with the ground in the event of an unsuccessful trip recovery. The safety harness was attached to an overhead track using a harness spreader bar, and the length of the spreader bar was adjusted such that the tips of the fingers were approximately two inches from the floor when reaching for the floor, and the knees (when flexed 90 degrees) were approximately two inches from the floor when allowing the harness to fully support body weight. Practice gait trials were performed along a 10 m walkway to allow participants to become accustomed to the experimental setup and procedures. Participants were given a starting position near one end of the walkway, and asked to walk at a slightly hurried speed with their eyes focused straight ahead. Speed was determined using a reflective marker on the medial border of the right scapula, and participants were asked to increase or decrease their speed if it was not 1.45-1.65 m/s (Table 6.1). Gait speed was controlled to prevent confounding effects, and because evidence suggests faster gait speeds are associated with an increased likelihood of falling following a trip (Pavol et al. 1999). Once accustomed, participants donned wireless headphones and watched a television program on computer monitors positioned at both ends of the walkway to divert attention from tripping. A message on the screen instructed the participant when to turn around and walk to the far end of the walkway. The starting position on the walkway was varied, and trials were repeated, until the dominant foot was naturally and consistently placed approximately 4 cm from the concealed tripping obstacle near the middle of the walkway. During a randomly selected trial, and upon this same foot placement relative to the obstacle, the trip obstacle was manually activated by pulling a concealed rope to raise the 7-cm-high obstacle and elicit a trip. All participants were successfully tripped.

Ground reaction forces were sampled at 1000 Hz from a force platform (Bertec Corporation, Columbus, OH) embedded in the walkway. Harness load was sampled at 1000 Hz using a uni-axial load cell (Cooper Instruments and Systems, Warrenton, VA). Both signals were low-pass filtered at 20 Hz (eighth-order zero-phase-shift Butterworth filter) using Matlab 2013a (The Mathworks Inc., Natick, MA). Body position was sampled at 100 Hz using a modified Helen Hayes marker set and a six-camera motion analysis system (MX-T10, Vicon Motion Systems Inc., L.A, CA), and subsequently low-pass filtered at 5 Hz (8th-order, zero-phase-shift Butterworth filter).

Harness load was used to classify trip recovery outcome as: 1) successful when peak force was less than 30% of participant body weight, and integrated harness force was less than 8% body weight × second (Brady et al. 2000) , 2) harness-assisted when peak force was 30-50% of participant body weight, and 3) unsuccessful when peak force exceeded 50% of participant body weight. Only two trials were deemed harness-assisted and were removed from further analysis. Harness load was also used to classify fallers as 1) before step fallers when the peak harness force occurred before touchdown of the first recovery step, and 2) after step fallers when the peak harness force occurred after touchdown of the first recovery step. All fallers were classified as after step fallers. Recovery step time was defined as the time elapsed from trip onset to touchdown of the first recovery step, where trip onset was identified by a peak in the acceleration of a marker on the 5th metatarsal head of the perturbed limb, and touchdown of the first recovery step was identified by a vertical ground reaction force greater than 15 N. Recovery step length was defined as the horizontal distance between markers on the right and left 5th metatarsal head at the time of the first recovery step. Trunk angle was defined as the angle between vertical and a line passing through markers on the right greater trochanter and the medial border of the right scapula. This angle was reported with respect to a reference angle calculated during a calibration trial where the participant stood in a natural up right position. Trunk angular velocity was calculated using a finite difference method. Peak trunk angle and angular velocity was identified between trip onset and toe off of the first recovery step. The position of the swing foot at trip onset was defined as the horizontal distance between markers on the right and left lateral malleolus.

Three statistical analyses were performed. Logistic regression analyses were used to investigate the effects of obesity, age, gender, and all two- and three-way interactions on fall rate and stepping strategy (elevating or lowering). A three-way analysis of variance was used to investigate the effects of obesity, age, gender, trip recovery outcome, and all two- and three-way interactions on recovery step time and length, peak trunk angle and angular velocity, and position of the swing foot at trip onset. Peak trunk angular velocity was log transformed in order to achieve normally distributed residuals. For all analyses, iterative backwards elimination was used to remove non-significant three-way then two-way interactions until only main effects and significant interactions remained in the final model. Following this procedure, no interactions remained in the final models for any of the dependent variables except for peak trunk angular velocity. Gender was included in the model to control for the reported effects of gender on trip recovery outcome (Pavol et al. 1999). A three-way analyses of variance was also performed to investigate the effects of obesity, age and gender on recovery step time and length when separately examining lowering and elevating strategies. All statistical analyses were performed using JMP 10 (SAS Institute Inc., Cary, NC) with a significance level of $p \leq 0.05$.

6.4 Results

Obesity affected several aspects of trip recovery. Fall rate was 52% among obese adults and 22% among normal-weight adults (Table 6.2), with an odds ratio indicating obese adults were 8.79 (C.I.: 4.62, 394.8; p=0.026) times more likely to fall when adjusting for age and gender. Stepping strategy (p=0.151), recovery step time (p=0.499), and recovery step length (p=0.854) were not affected by obesity (Table 6.3). Peak trunk angle was 13 degrees higher among obese adults (*p*=0.046) compared to normal-weight adults (Figure 6.1). Peak trunk angular velocity was affected by an obesity level x age interaction (*p*=0.038; Figure 6.1). Peak trunk angular velocity was 216 degrees/s higher among obese older adults compared to normal-weight older adults (*p*=0.012), and 245 degree/s higher among obese older adults compared to obese young adults (*p*=0.005).

Table 6.2: Fall rate separated by group. Note, N-W=normal-weight. * indicates *p*<=0.05.

	Fall	Recovery	Total	
Total	15	24	39	
Obese	11	10	21	*
N-W	4	14	18	
Older	12	6	18	*
Young	3	18	21	
Male	5	14	19	*
Female	10	10	20	

Table 6.3: Stepping strategy (number of occurrences), recovery step time and step length (mean ± standard deviation). Note: N-W=normal-weight. * indicates *p*<=0.05 between groups.

	Total	Elevating Strategy	Lowering Strategy		Recovery Step Time (s)	Recovery Step Length (m)
Obese	21	9	12		0.46 ± 0.16	0.73 ± 0.32
N-W	18	12	6		0.43 ± 0.13	0.72 ± 0.11
Older	18	6	12		0.46 ± 0.20	0.69 ± 0.34
Young	21	16	5	*	0.45 ± 0.09	0.75 ± 0.13
Male	19	13	6		0.43 ± 0.12	0.72 ± 0.27
Female	20	9	11		0.47 ± 0.16	0.74 ± 0.22
Falls	15	4	11	*	0.47 ± 0.21	0.74 ± 0.31
Recoveries	24	18	6		0.44 ± 0.08	0.72± 0.19

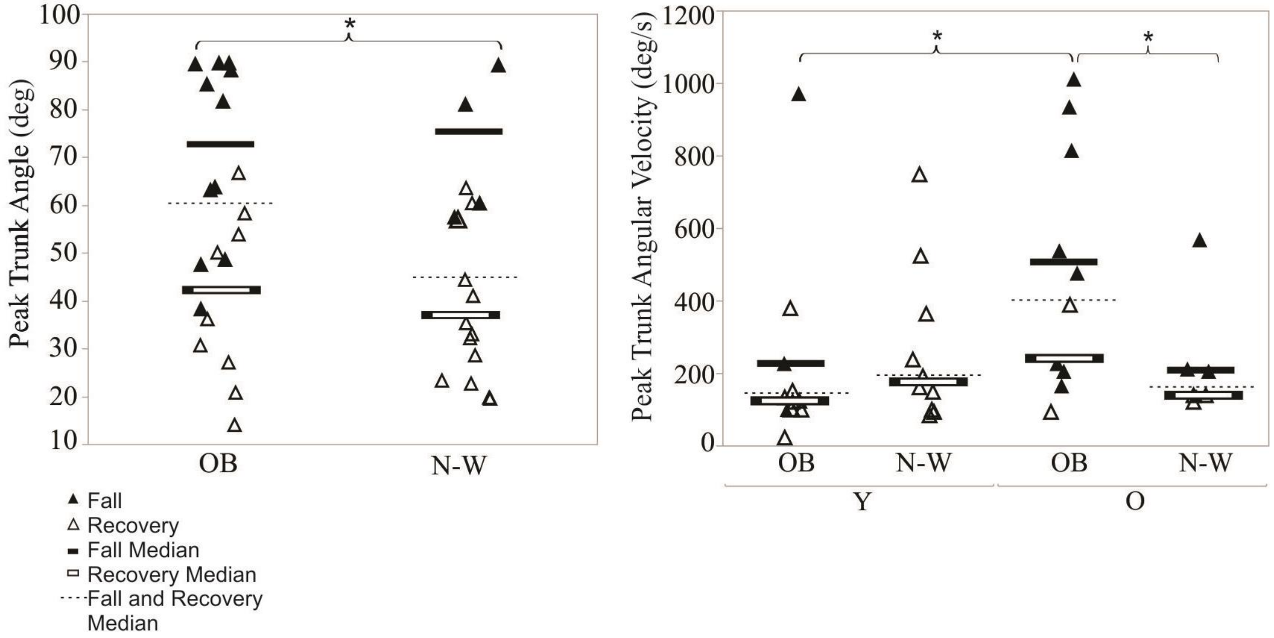

Figure 6.1: Peak trunk angle (left) and peak trunk angular velocity separated by obesity group, and obesity and age group, respectively. Brackets indicate *p*<0.05 between groups. Note: OB=obese, N-W=normal-weight, Y=young, O=older.

Age and gender also affected several aspects of trip recovery. Fall rate was 67% among older adults and 14% among young adults (Table 6.2), with an odds ratio indicating older adults were 30.24 (C.I.: 1.32, 100.39; *p*=0.001) times more likely to fall when controlling for obesity and gender. Fall rate was 50% among females and 26% among males, with an odds ratio indicating females were 8.17 (C.I.: 1.27, 89.4; *p*=0.047) times more likely to fall when controlling for obesity and age. A lowering strategy was used by 57% of older adults and 30% of young adults (Table 6.3), with an odds ratios indicating older adults were 8.63 (C.I.: 1.94:50.98; *p*=0.003) times more likely to use a lowering strategy when adjusting for obesity and gender. The effect of gender on stepping strategy approached significance when adjusting for obesity and age due to females tending to use a lowering strategy more frequently than males (*p*=0.077). Recovery step time and distance were not affected by age (*p*= 0.863 and *p*=0.431) or gender (*p*=0.403 and *p*=0.75; Table 6.3) when evaluating elevating and lowering strategies concurrently. When evaluating the two strategies separately, users of an elevating strategy exhibited a recovery step length that was 0.276 m shorter among older adults compared to young adults (*p*=0.003). Peak trunk angle was 25 degrees higher among older adults compared to young (*p*=0.001), and 17 degrees higher among females compared to males (*p*=0.013; Figure 6.3). As noted, peak trunk angular velocity was affected by an obesity level x age interaction (*p*=0.038; Figure 6.1) and was 136 degrees/second higher among females (*p*=0.002; Figure 6.3).

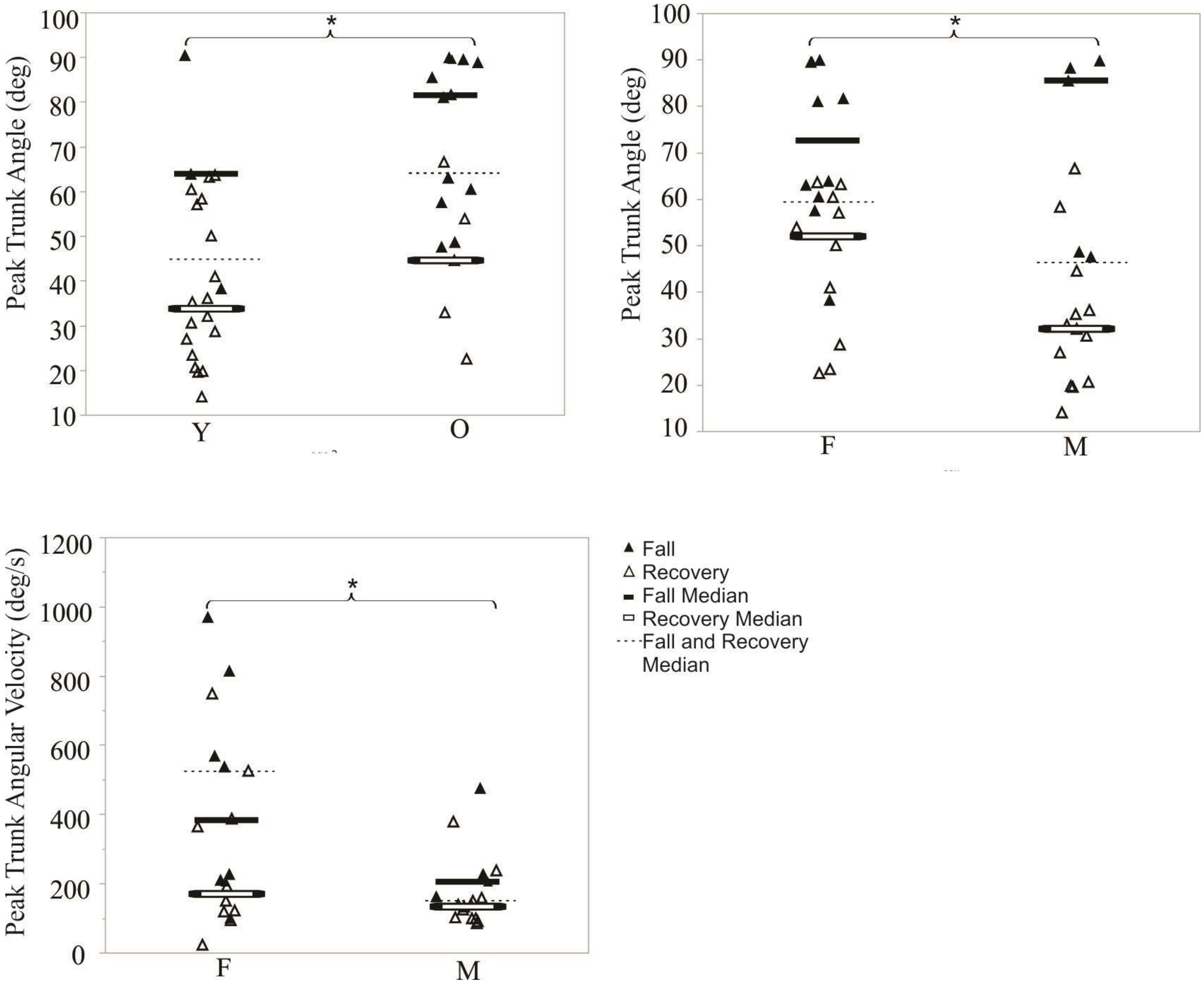

Figure 6.3: Peak trunk angle (top) and peak trunk angular velocity (bottom) separated by age group and gender. Brackets indicate *p*<0.05 between groups. Note: Y=young, O=older, F=female, M=male.

Comparing dependent variables between falls and recoveries also revealed several differences. A lowering strategy was used during 73% of falls and 25% of recoveries (Table 6.3) with odds ratios indicating users of a lowering strategy were 8.25 (C.I.: 2.03; 40.18; *p*=0.003) times more likely to fall then those using an elevating strategy (Table 6.2). Recovery step time and length

(Table 6.3) did not differ between falls and recoveries (*p*=0.541 and *p*=0.758). Peak trunk angle was 32 degrees higher during falls (*p*<0.001), and peak trunk angular velocity was 287 degrees/second higher during falls (*p*=0.027).

Gait speed averaged 1.55±0.14 m/s across all participants, and was not affected by obesity (*p*=0.689), age (*p*=0.368), gender (*p*=0.606), or trip outcome (*p*=0.980). Foot position at trip onset averaged 0.14±0.07 m and was not affected by obesity (*p*=0.345), age (*p*=0.481), gender (*p*=0.749), or trip outcome (*p*=0.664).

6.5 Discussion

The purpose of this study was to investigate the effects of obesity and age on trip recovery. Our first hypothesis was that obese adults would fall at a higher rate compared to normal-weight adults. This hypothesis was accepted because 52% of obese adults fell after tripping compared to only 22% of normal-weight adults. Our second hypothesis was that obese adults would exhibit less favorable stepping strategy/characteristics and/or trunk kinematics compared to normal-weight adults. This hypothesis was accepted because obese adults exhibited a greater peak trunk angle compared to normal-weight adults. Our third hypothesis was that the adverse effects of obesity would be magnified among older adults. This hypothesis was accepted because the effect of obesity on peak trunk angular velocity was magnified among older adults. These results suggest that the higher fall rate among obese adults may be due, to some extent, to impaired trip recovery. Several other effects of age, gender, and trip outcome were also found and described in more detail below. Overall, these results support the use of interventions to improve trip recovery capability to help prevent falls among individuals who are obese, older, or female.

The fall rates among obese (52%) and normal-weight (22%) adults in the current study were similar to those reported by Rosenblatt and Grabiner (2012) for obese (46%) and normal-weight (25%) female adults aged approximately 55-65 years. Fall rates among older adults (67%) and females (50%) in the current study were similar to those reported by Pavol *et al.* (1999) (62% among older adults, 22% among females), and Pijnappels *et al*. (2005) (63% among older adults). The lack of an effect of age on recovery step length and time in the current study differed from the shorter recovery step lengths (Schillings et al. 2005) and longer recovery step times (Pijnappels et al. 2005) among older adults reported elsewhere. However, both Schilling *et al* (2005) and Pijnappels *et al* (2005) tripped participants multiple times during the same experimental session, which may have altered recovery techniques due to learning and anticipation effects following the first trip. Similar to the current study, Pavol *et al* (2001) investigated kinematic differences between falls and recoveries. The current study reported peak trunk angle to be 32 degrees higher during falls compared to recoveries, which was comparable to the 54.7 degrees higher peak trunk angle during falls reported by Pavol *et al.* (2001). However, the 287 degree/second higher trunk angular velocity was substantially higher than the 83.5 degrees/second reported by Pavol *et al.* (2001). The larger difference in trunk angular velocity in the current study may be due, in part, to differences in protocol (hurried controlled gait speed vs. self-selected gait speed) and participant demographics (including young, older, obese and normal-weight participant vs including only older normal-weight participants).

The higher rate of falls among obese adults may have resulted from altered trunk kinematics. Obese adults exhibited greater peak trunk angles compared to normal-weight adults, and older obese adults exhibited greater peak trunk angular velocities compared to older normal-weight adults. A lower trunk angle and angular velocity is indicative of more effective trip recovery as it aims to reduce the forward velocity of the COM and to bring the COM back to within the limits of the base of support. Three intrinsic factors associated with obesity could be responsible for these altered kinematics. First, the anterior shift of the trunk COM among obese adults could increase the gravitational moment that rotates the body forward after tripping (Corbeil et al. 2001), and this larger gravitational moment could increase trunk angle and angular velocity. Second, greater trunk mass would increase trunk momentum that needs to be decelerated through trunk and lower extremity muscle exertions (Pijnappels et al. 2004). Third, reduced relative strength among obese adults (Hulens et al. 2001, Lafortuna et al. 2005, Maffiuletti et al. 2007) could reduce the ability to decelerate trunk momentum. Interestingly, the higher rate of falls among obese adults was not likely due to altered stepping characteristics because there were no differences in recovery step time, recovery step length, or stepping strategy between obese and normal-weight adults.

As with obese adults, the higher rate of falls among older adults and females may have resulted from altered trunk kinematics. Older adults and females displayed greater peak trunk angles, and older obese adults and females displayed greater peak trunk angular velocities. Older adults and females are also reported to have decreased strength compared to their younger (Goodpaster et al. 2006) and male counterparts (Frontera et al. 1991) likely inhibiting control of trunk kinematics. As with obesity, the higher rate of falls among older adults and females was not likely due to differences in recovery step time or recovery step length, but may be due in part to the more frequent use of a lowering strategy which was shown to be unfavorable with respect to recovery outcome. Stepping strategy affects stepping characteristics. For example, elevating strategies have been reported to elicit longer recovery step lengths and shorter step timing compared to lowering strategies (Eng et al. 1994). The analysis examining stepping characteristics which separated users of elevating and lowering strategies revealed that among users of an elevating strategy, recovery step length was 0.276 m shorter among older adults compared to young adults, which is consistent with earlier reports exclusively examining elevating strategies (Schillings et al. 2000 Pijnappels, 2005 #101). Whether this alteration contributed to the increased fall rate among older adults is unclear and should be examined further.

The success of trip recoveries during the near-mid-swing trips induced here appears to be fairly dependent upon the choice of stepping strategy. For example, 73% of trials involving a lowering strategy resulted in a fall whereas only 25% of trials involving an elevating strategy resulted in a fall. Moreover, older adults and females who exhibited higher fall rates both tended to use a lowering strategy more frequently than their young or male counterparts. Other studies have reported a higher prevalence of lowering strategy among older adults (Pavol et al. 2001) and obese adult fallers (Rosenblatt and Grabiner 2012). For older adults it has been shown that practicing balance recovery from a simulated trip improves recovery kinematics following an actual trip (Bieryla et al. 2007, Grabiner et al. 2012). This training may be effective in promoting more frequent use of the elevating strategy during mid-swing trips.

Recovery step time and length exhibited practically no effects of obesity, age, and gender, and even exhibited no differences between falls and recoveries. This was unexpected given others have reported a longer step time (Pijnappels et al. 2005) and shorter step length among older adults (Pijnappels et al. 2005, Schillings et al. 2005) and among falls compared to recoveries (Pavol et al. 2001). The recovery step is crucial in arresting the whole body angular momentum induced by the trip by extending the base of support anteriorly, and providing vertical and posterior ground reaction forces. These results suggest other aspects of trip recovery, besides recovery step time and length, have a large influence on whether balance is successfully recovered. Two possible other aspects of trip recovery include stance leg contributions to both decelerate trunk kinematics while stepping (Pijnappels et al. 2004) and the support phase of balance recovery after completing the recovery step (Madigan and Lloyd 2005). As noted above, balance recovery training has the potential to improve these aspects of trip recovery to make stepping more effective.

There are several limitations to this study that warrant discussion. First, participants were informed that they may be perturbed to elicit a trip or slip during any walk down the walkway. As such, anticipation effects may have existed. However, several precautions were taken to reduce this effect including, distractions (watching television) and ample time between the start of testing and the induced trip. Second, as with any cross sectional study, other differences between groups besides the characteristics reported here could have contributed to the results. Third, skin movement artifacts are typically exaggerated in obese individuals due to increased adipose tissue which could cause errors in kinematic data. However, care was taken in securing thigh and sacrum clusters to the participant to avoid such movement.

6.6 Conclusions

Obese adults fell more frequently after tripping compared to normal-weight counterparts, and had higher peak trunk angles and angular velocities. This higher fall rate may help explain the higher fall rates among obese adults reported elsewhere. Older and female adults also fell more frequently after tripping compared to their young and male counterparts, which may also explain the higher fall rates among older adults and females reported elsewhere. Failed recoveries were associated with higher peak trunk angles and angular velocities in addition to the use of a lowering strategy. Obese, older, and female adults had higher peak trunk angles and angular velocities and older adults and females used lowering strategies more often. These alterations in trunk kinematics and stepping strategy may have contributed to the higher fall rate among these individuals. Surprisingly, recovery step length and time did not differ with obesity, age, gender, or between falls and recoveries.

6.7 Acknowledgements

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6.8 References

Berg, W. R., H. M. Alessio, E. M. Mills and C. Tong (1997). "Circumstances and consequences of falls in independent community dwelling older adults." Age Ageing **26**(4): 261-68.

Bieryla, K. A., M. L. Madigan and M. A. Nussbaum (2007). "Practicing recovery from a simulated trip improves recovery kinematics after an actual trip." Gait & posture **26**(2): 208-13.

Blake, A. J., K. Morgan, M. J. Bendall, H. Dallosso, S. B. J. Ebrahim, T. H. D. Arie, P. H. Fentem and E. J. Bassey (1998). "Falls by elderly people at home - prevalence and associated factors." Age Ageing **17**(6): 365-72.

Brady, R. A., M. J Pavol, T. M. Owings and M. D. Grabiner (2000). "Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking." Journal of biomechanics **33**(7): 803-08.

Corbeil, P., M. Simoneau, D. Rancourt, A. Tremblay and N. Teasdale (2001). "Increased risk for falling associated with obesity: Mathematical modeling of postural control." Neural Systems and Rehabilitation Engineering, IEEE Transactions on **9**(2): 126-36.

Eng, J. J., D. A. Winter and A. E. Patla (1994). "Strategies for recovery from a trip in early and late swing during human walking." Experimental Brain Research **102**: 339-49

Finkelstein, E. A., H. Chen, M. Prabhu and J. G. Trogdon (2007). "The relationship between obesity and injuries among u.S. Adults." American journal of health promotion **21**(5): 460-8.

Fjeldstad, C., A. S. Fjeldstad and L. S. Acree (2008). "The influence of obesity on falls and quality of life." Dynamic Medicine **7**(4).

Frontera, W. R., V. A. Hughes, K. J. Lutz and W. J. Evans (1991). "A cross-sectional study of muscle strength and mass in 45-to 78-yr-old men and women." Journal of applied physiology **71**(2): 644-50.

Goodpaster, B. H., S. W. Park, T. B. Harris, S. B. Kritchevsky, M. Nevitt, A. V. Schwartz, E. M. Simonsick, F. A. Tylavsky, M. Visser and A. B. Newman (2006). "The loss of skeletal muscle strength, mass, and quality in older adults: The health, aging and body composition study." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **61**(10): 1059-64.

Grabiner, M. D., M. L. Bareither, S. Gatts, J. Marone and K. L. Troy (2012). "Task-specific training reduces trip-related fall risk in women."

Grabiner, M. D., T. J. Koh, T. M. Lundin and D. W. Jahnigen (1996). "Kinematics of recovery from a stumble." Journal of Gerontology **48**(3): M97-M102.

Hulens, M., G. Vansant, R. Lysens, A. Claessens, E. Muls and S. Brumagne (2001). "Study of differences in peripheral muscle strength of lean versus obese women: An allometric approach." International Journal of Obesity Related Metabolic Disorder **25**(5): 676-81

Lafortuna, C. L., N. A. Maffiuletti, F. Agosti and S. A. (2005). "Gender variations of body composition, muscle strength and power output in morbid obesity." International Journal of Obesity **29**(7): 833-41.

Madigan, M. L. and E. M. Lloyd (2005). "Age-related differences in peak joint torques during the support phase of single-step recovery from a forward fall." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **60**(7): 910-14.

Madigan, M. L. and E. M. Lloyd (2005). "Age and stepping limb performance differences during a single-step recovery from a forward fall." The Journals of Gerontology Series A: Biological Sciences and Medical Sciences **60**(4): 481-85.

Maffiuletti, N. A., M. Jubeau, U. Munzinger, M. Bizzini, F. Agosti, A. De Col, C. L. Lafortuna and A. Sartorio (2007). "Differences in quadriceps muscle strength and fatigue between lean and obese subjects." European Jounral of Applied Physiology **101**(1): 51-9.

Ogden, C. L., M. D. Carroll, B. K. Kit and K. M. Flegal (2014). "Prevalence of childhood and adult obesity in the united states, 2011-2012." Journal of the American Medical Association **311**(8): 806-14.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (1999). "Gait characteristics as risk factors for falling from trips induced in older subjects." Journal of Gerontology: Medical Sciences **54A**: M583-M81.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (1999). "The sex and age of older adults influence the outcome of induced trips." Journal of Gerontology: Medical Sciences **54A**(2): M103-08.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (2001). "Mechanism leading to a fall from an induced trip in healhty older adults "

Journal of Gerontology: Medical Sciences **56A**(7): M428-M37.

Pavol, M. J., T. M. Owings, K. T. Foley and M. D. Grabiner (2002). "Influence of lower extremity strength of healthy older adults on the outcome of an induced trip." Journal of American Geriatric Society **50**(2): 256-62.

Pijnappels, M., M. F. Bobbert and J. H. v. Dieën (2005). "Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers." Gait & Posture **21**(4): 388-94.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2004). "Contribution of the support limb in control of angular momentum after tripping." Journal of Biomechanics **37**(12): 1811-18.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2004). "Control of support limb muscles in recovery after tripping in young and older subjects

" Experimental Brain Research **160**(3): 326-33.

Pijnappels, M., M. F. Bobbert and J. H. van Dieën (2005). "How early reactions in the support limb contribute to balance recovery after tripping." Journal of Biomechanics **38**(627-34).

Pijnappels, M., N. D. Reeves, C. N. Maganaris and J. H. van Dieën (2008). "Tripping without falling; lower limb strength, a limitation for balance recovery and a target for training in the elderly." Journal of Electromyography and Kinesiology **18**(2): 188-96.

Pijnappels, M., N. D. Reeves and J. H. van Dieën (2008). "Identification of elderly fallers by muscle strength measures." European journal of applied physiology **102**(5): 585-92.

Rosenblatt, N. J. and M. D. Grabiner (2012). "Relationship between obesity and falls by middle-aged and older women." Archives of Physical Medicine and Rehabilitation **93**(4): 718-22.

Schillings, A., T. Mulder and J. Duysens (2005). "Stumbling over obstacles in older adults compared to young adults." Journal of neurophysiology **94**(2): 1158-68.

Schillings, A., B. Van Wezel, T. Mulder and J. Duysens (2000). "Muscular responses and movement strategies during stumbling over obstacles." Journal of Neurophysiology **83**(4): 2093-102.

Van den Bogert, A. J., M. J. Pavol and M. D. Grabiner (2002). "Response time is more important than walking speed for the ability of older adults to avoid a fall after a trip." Journal of Biomechanics **35**(2): 199-205.

Wang, Y. and M. A. Beydoun (2007). "The obesity epidemic in the united states—gender, age, socioeconomic, racial/ethnic, and geographic characteristics: A systematic review and meta-regression analysis." Epidemiologic Reviews **29**(1): 6-28.

WHO. (2007). "World health orginization, global report on falls prevention in older age." Retrieved May 7, 2014, from http://www.who.int/ageing/publications/Falls_prevention7March.pdf.

Chapter 7: Conclusion

7.1 Summary

Four experimental studies were completed to evaluate the effects of obesity and age on the likelihood of tripping and subsequent balance recovery. The first study (Chapter 3) investigated the effects of obesity, age and gender of the likelihood of tripping during level walking through measures of median minimum foot clearance (MFC) and MFC interquartile range (IQR). There was no substantial influence of obesity on the likelihood of tripping during level walking. As such, the higher rate of falls among individuals who are obese does not appear to be due to a greater likelihood of tripping. Other novel results from this study suggest an increased likelihood of tripping among females and individuals of shorter stature.

The second study (Chapter 4) investigated the effects of load carriage and ramp walking on the likelihood of tripping, and the effects of obesity and age on the likelihood of tripping during load carriage and ramp walking. Again median MFC and MFC IQR were used as descriptive measures for the likelihood of tripping. Load carriage increased the likelihood of tripping during both level and ramp walking. Advanced age increased the likelihood of tripping during ramp descent and both obesity and advanced age increased the likelihood of tripping during ramp ascent with load carriage. These results suggest that the increased rate of falling during load carriage and the increased rate of falling among obese and older adult workers reported elsewhere may be due in part to an increased risk of tripping.

The third study (Chapter 5) proposed a new method to investigate the likelihood of tripping as a function of obstacle height that clears up ambiguous results often encountered when using MFC central tendency and variability. The method involved creation of trip probability curves and the use of a statistical bootstrapping technique to compare trip probability at specific obstacle heights between groups of interest. In addition to clearing up ambiguities the method was also able to identify effects of factors not identifiable by the commonly used ANOVA analysis using MFC central tendency and variability.

The fourth study (Chapter 6) evaluated the effects of obesity, age and gender on balance recovery following a lab induced trip perturbation. Fall rate, trunk kinematics and stepping characteristics were investigated as measures of balance recovery. Obese, older, and female adults fell more frequently after tripping and this higher fall rate may help explain the higher fall rates among obese, older and female adults reported elsewhere. Other novel results revealed failed recoveries were associated with higher peak trunk angles and angular velocities in addition to the use of a lowering strategy. Obese, older, and female adults had higher peak trunk angles and angular velocities and older adults and females used lowering strategies more often. These alterations in trunk kinematics and stepping strategy may have contributed to the higher fall rate among these individuals.

The goal of this dissertation was to better understand the mechanisms contributing to the increased risk of falling among obese and older adults during every day and occupational tasks. There are three main contributions of this research. First, this was the first study to examine the effects of obesity and obesity x age interactions on the likelihood of tripping and balance recovery following a trip. Results suggested that the increased fall rate reported elsewhere among obese and older adults is likely due in part to an impaired ability to recover balance after tripping and less likely due to an increased risk of tripping while walking. Secondly, this research identified and rectified issues concerning commonly used ANOVA analyses using MFC central tendency and variability to quantify the likelihood of tripping. The developed method has the advantage of identifying specific obstacle heights at which differences in trip probability exist between groups of interest which may be helpful for various trip and fall prevention strategies. Lastly, understanding the mechanisms that contribute to increased fall rates among obese and older adults could aid in the development of inclusive safety standards for the increasing populations of obese and older adults in addition to help identify modifiable risk factors for targeted interventions.

7.2 Expected Publications

Table 7.1: Expected publications from studies. Note: * In Review

Chapter	Title	Journal
3	Minimum foot clearance during overground walking is lower among females but does not differ with obesity	Journal of Electromyography and Kinesiology*
4	The effects of obesity and age on minimum foot clearance during occupationally relevant tasks	Gait and Posture
5	A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height	Journal of Biomechanics* (short communication)
6	Obesity and advanced age increase fall rate following a laboratory-induced trip	Gait and Posture

7.3 Future Work

Further research is warranted to better understand the effects reported here. There are several issues concerning the use of MFC as a descriptive measure for likelihood of tripping. First, to the best of our knowledge no studies have correlated measures of MFC with actual trip occurrence. Second, both the bootstrapping method and the median MFC and MFC IQR method depend only upon foot clearance at the instant MFC occurs, even though a trip could occur at other instances during the swing phase. Once these issue are rectified, analysis on the effects of obesity and age on likelihood of tripping should be reexamined. With respect to balance recovery following a trip, a deeper analysis should be conducted investigating additional variables such as joint moment and power in the stance and recovery limbs, whole body angular momentum, and muscle activation and response timing. This would allow a better understanding of the mechanisms involved in failed recoveries and further identify modifiable risk factors for targeted interventions. Research is underway to address these issues and enhance our understanding of the effects of age and obesity on likelihood of tripping and subsequent balance recovery.