A Study on the Effects of Obesity and Age on Balance Recovery after Slipping

Leigh Jouett Allin

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of:

Master of Science
in
Engineering Mechanics

August 1, 2014
Blacksburg, VA

Michael L. Madigan, Chair
Maury A. Nussbaum
Jake J. Socha

Keywords: biomechanics, slips and falls, aging, obesity

A Study on the Effects of Obesity and Age on Balance Recovery after Slipping

Leigh Jouett Allin

Abstract

Falls due to slipping are a serious occupational concern. Slipping is estimated to cause 40-50% of all fall-related injuries. In 2011, falls resulted in 22% of injuries requiring days away from work. Epidemiological data indicates that older and obese adults experience more falls than young, non-obese individuals. An increasingly heavier and older workforce may be exacerbating the problem of slip-induced falls in the workplace. The purpose of this study was to examine the effects of obesity and age on slip severity and fall outcome following an unexpected slip. Four groups of participants (young obese, young non-obese, older obese, older non-obese) were exposed to an unexpected slip perturbation. Slip severity (slip distance, slip duration, average slip velocity and peak slip velocity) and slip outcome (fall or recovery) were compared between groups.

Obese individuals experienced 8.25% faster slips than non-obese individuals in terms of average slip velocity (p=0.022). Obesity did not affect slip distance, slip duration or peak slip velocity. Obese individuals also experienced more falls; 33.3% of obese individuals fell compared to 8.6% of non-obese (p=0.005). Obese individuals were 8.24 times more likely to experience a fall than non-obese individuals, when adjusting for age, gender and gait speed. No age effects were found for slip severity or slip outcome. This study revealed that obese participants experienced faster slips and more falls than their non-obese counterparts. These results, along with epidemiological data reporting higher fall rates among the obese, indicate that obesity may be a significant risk factor for experiencing slip-induced fall.

Funding organization:
Centers for Disease Control, National Institute for Occupational Safety and Health
R01OH009880

Acknowledgements

First, I would like to thank Dr. Madigan. A little over a year ago, I decided to enter the field biomechanics. Thank you for the opportunity to work in your lab and become involved in this project on slip biomechanics. You have taught me everything I know about biomechanics—how to use the equipment, design an experiment, collect and analyze data. This wouldn't have been possible without you.

Next, I would like to thank Dr. Nussbaum and Dr. Socha for serving on my advisory committee. Dr. Nussbaum, thank you for providing advice and feedback on my abstracts. Dr. Socha, thank you for sparking my interest in bioengineering during your undergraduate class.

Thank you to my lab-mates: Tina, Hoda, Xuefang, John, Abi, and Jaclyn. Thank you for always being friendly, patient, and helpful. I've really enjoyed working with all of you in the lab. I'd especially like to thank Xuefang for working closely with me on this study. Also, thank you to John and Tina, who helped with data collections when I was away at track meets. It's been a busy year, and I couldn't have finished this project without your help.

Thank you to my parents for your continued support throughout all of my endeavors. Thank you to Bob, my pole vault coach, who allowed me to continue competing this past year. Thank you to my brother, grandparents, teammates, friends, professors, and anyone else who has helped me along the way. I'm lucky to have had this support system.

Table of Contents

List of Figures & Tables

Chapter 1 – Overview & Motivation

Falls due to slipping are a significant problem in the workplace, and cause a substantial proportion of occupational injuries requiring days away from work. In addition, the United States population is becoming increasingly heavier and older, and obese and older adults are reported to experience more falls and sustain more injuries from falling compared to their young, non-obese counterparts. Based on this observation, this study seeks to understand the effects of obesity and age on slip-induced fall risk. Identifying obesity and/or age as factors contributing to slip-induced falls could lead to better standards for preventing slip-induced falls in occupational settings.

This thesis documents the motivation, background, and details of a biomechanical experiment on human subjects investigating the effects of obesity and age on slips and falls. Chapter two provides background on prior research on the biomechanics of slips and falls, including underlying biomechanical and physiological factors contributing the to these accidents. Chapter three is a self-contained manuscript that describes the research study on the affects of obesity and age on slip severity and slip-induced fall risk.

Chapter 2 – Introduction

Slips, trips, and falls are a significant occupational safety hazard.[1] Falls were the leading cause of emergency room visits in 2007, accounting for 23% of all injury-related visits.[2] The consequences of slips, trips, and falls can range from mild to severe. Medical consequences can include sprains, strains, fractures, bruises, contusions, brain trauma, and even death.[3] Other consequences are less tangible, and can involve a loss of mobility, reduced confidence, and chronic fear of falling.[4] The National Institute of Health claims that slipping, tripping or stumbling contributes to 64% of all falls.[3] Furthermore, slips, trips and falls accounted for 553 occupational fatalities, and 22% of injuries requiring days away from work in 2011.[5] These injuries required a median of 11 days of recovery before returning to work.[6] The annual cost of fall-related injuries in the U.S. is estimated to be a staggering $5.7 billion, which makes falls due to slipping and tripping a serious problem within occupational settings.[7] Reducing the frequency of falls in the workplace can have a significant economic impact, as well as improve health and safety in the workplace.

Biomechanics of Slips

Slips are described as a loss of traction at the shoe-floor interface and often result in a backwards loss of balance.[8] Slips can be caused by a variety of environmental and physiological factors. Environmental—or extrinsic—factors include spilled contaminants, weather conditions, loose rugs, surface roughness, and footwear characteristics.[4,8,9] Spilled liquid or an icy sidewalk can dramatically reduce shoe-floor friction, and leads to a large proportion of slips. Certain footwear can influence postural stability or reduce friction at the shoe-floor interface.[9] Walking barefoot, in slippers, or in hard-soled shoes have been shown to increase the risk of falling from a slip.[9-11] Physiological—or intrinsic—factors include muscle weakness, gait and balance problems, visual impairment, cognitive impairment, depression, functional decline, and certain medications.[4] Combinations of these extrinsic and intrinsic factors can increase a person's propensity for slipping as well as their likelihood of falling and sustaining an injury from a slip. It is hypothesized that physiological differences accompanying obesity and age can affect a person's ability to recover from a slip perturbation.[4,12,13]

Slip Initiation

Frictional properties at the shoe-floor interface are critical parameters leading to a slip event.[8,14] Traction while walking depends on a relationship between the required coefficient of friction (RCOF) for walking and available friction between the shoe and floor; if the required friction matches or exceeds the available friction, a slip is inevitable.[14] RCOF is defined as the ratio of shear and normal ground reaction forces (GRF) during normal gait. The shear and normal GRFs are defined by two large peaks: the first peak occurs 90-150 ms after heel contact, while the second peak occurs just before toe-off. The first peak in shear force is considered to be the critical peak for slip events. This peak occurs in the forward direction, when the person's weight is transferred onto the stepping foot. The second peak can also be associated with slipping. This peak occurs is the rearward direction, when the heel is pushed off of the floor to initiate the toe-off phase.[14] Most slips occur at the first peak in RCOF, as this is where weight is initially transferred onto the stance foot. Higher RCOF is linked to a higher likelihood of slipping. Slips are often caused by extrinsic factors, but a person's ability to recover their balance after a slip can be largely affected by intrinsic factors, such as physiological conditions and gait kinematics. Researchers have investigated the biomechanical mechanisms leading to slips and slip-induced falls, and have found a variety of parameters to estimate slip risk and quantify slip severity.

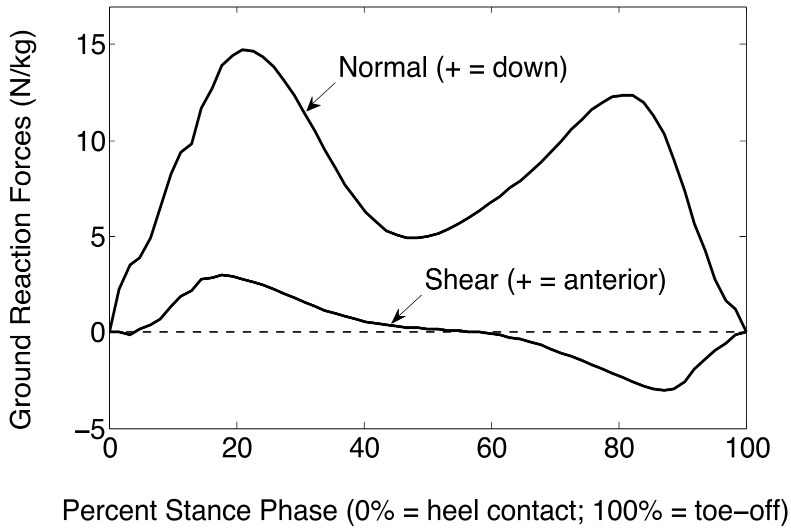

Figure 1. Shear and normal GRFs during level walking

Quantifying Slip Risk & Severity

Studies have investigated the biomechanical mechanisms leading to slip-induced falls, and have suggested that certain gait parameters can influence a person's risk of slipping and falling. Gait speed has been found to influence slip risk; faster walkers tend to experience more slips and falls. Faster walking decreases dynamic postural stability—a key component for maintaining balance.[15] However, evidence is inconclusive that gait speed increases a person's risk of falling from a slip.[16] Step length can also impact slip propensity, as longer steps result in greater shear forces at heel contact and increased RCOF.[17] This increase in RCOF is likely due to higher foot angles at heel contact.

Gait kinematics at heel contact can also have a pronounced impact on slip risk. Studies have revealed an influence of heel contact angle on slip outcome, with falls exhibiting more dorsiflexion at heel contact.[16] Lower foot angles and increased knee flexion at heel contact are associated with lower RCOF, and subsequently lower slip risk.[18] Studies have shown that when walking on slippery surfaces, participants tend to walk with more knee flexion and lower foot angles at heel contact to reduce RCOF.[18,19] Following the onset of a slip, kinematic parameters can be used to quantify the severity of a slip and predict the outcome. Brady, et al. (2000) measured slip severity using slip duration, slip displacement, and peak and average slipping foot velocity. He concluded that slip displacement provided the best prediction of slip outcome, since longer slips are more likely to result in falls than shorter slips. He also found that walking speed was not an important factor in predicting the outcome of a slip. Average slipping foot velocity, slip duration, and heel-strike angle were also associated with a higher fall rate.[16] Bakken & Hyde (2001) classified slip-induced falls as having four common types of outcomes: (1) both feet immediately slide forward; (2) the leading foot slips forward and the trailing foot stays behind, eventually slipping forward; (3) the leading foot slips forward and the trailing foot stays behind, resulting in a split position; (4) the leading foot slips sideways, as the body is rotated in an attempt to change the direction of movement.[20]

Balance Recovery After a Slip

Following a slip event, a quick corrective response is required attempt to restore the body's balance over the base of support.[14] A variety of corrective actions can be adopted in response to a slip perturbation. Corrective responses can involve arm swinging, hip or ankle strategy, compensatory stepping, or trunk movement.[14,21,22] Backward falls typically occur when balance is not restored after slipping. The outcome of a slip is highly dependent on gait biomechanics, physiological conditions, and environmental factors, and successful balance recovery depends on the magnitude and timing of these responses.[14,23]

Moyer, et al. (2009) identified four main strategies used in response to a slip, based on trailing leg kinematics: (1) the trailing leg follows a swing phase similar to normal walking; (2) the entire sole of the trailing foot contacts the ground near or just behind the slipping foot; (3) the sole of the trailing foot contacts the ground, but more posterior to the slipping foot; (4) the toe of the trailing foot contacts the ground rapidly following toe-off. These trailing leg responses were coupled with increased knee flexion and hip extension in the slipping leg.[24] Cham and Redfern (2001) investigated corrective reactions to slip events, and found that corrective reactions are characterized by increased knee flexion and hip extensor moments in the slipping leg. The ankle acted passively during fall trials. The onset of these corrective reactions occurred during approximately 25-45% of the stance phase, or 190-350ms after heel contact.[25] The increased knee flexion is thought to rotate the shank forward to restore the body center of mass over the base of support, while hip extensor moments are used to maintain upright posture during recovery.[14,26] Studies have also shown the use of an ankle strategy, during which an ankle dorsiflexion moment attempts to rotate the shank over the base of support.[26]

Researchers have used a variety of methods for classifying slips in a laboratory as falls or recoveries. Slip experiments in a research lab typically involve participants wearing a torso harness to prevent a fall to the ground in the event of an unsuccessful balance recovery. The most common method to distinguish falls and recoveries is to use the peak load recorded by the harness load cell (as percent body weight) and/or the integrated harness load over the duration of the slip and recovery (as percent body weight × second). Brady, et al. (2000) classified slip trials as falls if the peak harness load exceeded 50% of the participant's body weight; recoveries were classified as having integrated harness loads of less than 8% body weight × second. Trials with a peak harness load less than 50% body weight and an integrated harness load greater than 8% body weight were more difficult to clearly characterize as a fall or recovery, and thus were considered “rope-assisted” and excluded from further analysis.[16] You, et al. (2001) classified a slip trial as a fall if the subject exerted 18.5% or more of their body weight into the harness.[27] Pavol, et al. (2001) described trials as falls if the harness load exceeded 50% body weight at any instance following a trip perturbation.[28] Yang, et al. (2011) classified slip trials as falls if the peak harness load exceeded 30% participant body weight, and recoveries if the average harness force never surpassed 4.5% body weight over any 1-second interval.[29] Although no universal criterion exists for distinguishing falls from recoveries using harness load data, most researchers use a threshold of 30-50% body weight to classify trials as falls. A conservative approach is to exclude ambiguous trials exhibiting moderate harness loads, as outcomes for these trials are unclear.

Obesity and Fall Risk

Demographic trends show the United States workforce becoming increasingly obese. Based on standards set by the U.S. Centers for Disease Control, a person is considered obese if they have a BMI of 30 kg/m^2 or greater. In 2012, 35.1% of adults over 20 in the U.S. were reported to be obese.[30,31] The highest proportion of obese adults was found between the ages of 40-59 years, for which 39.5% were reported to be obese. For adults over 60 years old, 35.4% were reported to be obese.[32] Overweight and obese individuals are at risk for developing medical conditions such as hypertension, high blood cholesterol, type II diabetes, and coronary heart disease.[33]

Overweight (BMI $\geq$ 25 kg/m^2) and obese individuals experience more falls than their non-obese counterparts,[12,34] and obesity is linked to an overall higher risk of suffering occupational injury, particularly from slipping, tripping, stumbling, and falling.[35] Rosenblatt and Grabiner (2012) found that obese women over 55 fell at a higher rate than their non-obese counterparts when exposed to a laboratory-induced trip.[36] In the same study, a retrospective analysis revealed that obese women did not experience a higher number of self-reported falls as non-obese women. Obese women also reported more injuries than non-obese women, leading to the belief that obesity may heighten a person's risk of sustaining an injury from falling. Compared to non-obese, a higher proportion of emergency room visits from obese individuals are due to injuries relating to sprains and strains, which are often fall-related.[37]

A higher risk of falling among the obese may be caused by certain physiological and biomechanical factors. Obese adults tend to walk at slower self-selected speeds, with shorter strides at lower frequencies.[38] These gait characteristics are normally associated with higher stability, but it is suggested that these gait alterations are indicative of more obesity-related instabilities. Postural stability is a common measure used to quantify balance control. Hue, et al. (2007) found a strong correlation between increased body mass and decreased postural stability.[39] Wu, et al. (2012) examined risk of slipping among young obese males, and found increases in RCOF in the transversal direction for obese individuals. This result indicates a higher risk of slipping in the mediolateral direction but not the anteroposterior direction, which may be attributed to shorter, wider steps.[40] Research also suggests that obese individuals have lower plantar sole sensitivity, which can reduce the ability to detect and respond to the onset of a slip.[41] Additionally, whether due to low physical activity or other factors, obese individuals often exhibit muscle strengths that are lower than their non-obese counterparts, when adjusting for weight.[42] Weakness in the lower extremities can increase one's likelihood of experiencing a fall and fall-related injury. Mechanisms influencing slip-induced fall rates among the obese are still largely unclear, and more research should assess the causal mechanisms for slip-related falls and injuries among the obese.

Age and Fall Risk

The effect of age on fall risk is an important issue since demographic trends show the United States workforce is getting progressively older. From 1998-2008, adults aged 55 and older increased by 16 million, and is projected to increase by nearly 21 million from 2008-2018.[43] The labor force participation rate for adults 55-64 increased from 61.9% to 64.5% between 2002 and 2012, and this proportion is expected to increase to 67.5% by 2022.[44] Older adults are at a higher risk of experiencing serious consequences from falling, as falls are leading cause of accidents and the fifth leading cause of death for adults over 65 years old.[45]

Aging leads to declines in muscle strength, cardiovascular health, impaired vision, loss of coordination, slower reflexes, and vertigo, all of which are associated with a heightened risk of falling. [4,46] Additional age-related conditions increase the risk of sustaining a serious injury from a fall, including arthritis, diabetes, and osteoporosis. An observational study of community-dwelling older adults reported that 6% of all falls resulted in fractures, and 22% of those falls were caused by slipping.[47] Hip fractures often result from falls, and can inhibit mobility for older adults.[47]

Older adults tend to show more cautious gait patterns, walking with shorter steps and slower self-selected speeds.[4,48] In spite of these cautious gait adaptations, older adults are reported to slip and fall more often from unexpected slip perturbations compared to their younger counterparts.[49] Researchers have investigated the mechanisms leading to their increased fall risk. Lockhart et al. (2003) reported that older adults exhibit faster heel contact velocities and slower transitional accelerations of the body center of mass over the slipping foot.[50] Gait patterns in older adults tends to be stiffer and less coordinated, leading to a decrease in postural stability.[4] Postural sway is a measure that is commonly used to quantify balance. Hasselkus, et al. (1975)

found significant increases in postural sway area for older women, when compared to their younger counterparts.[51]

Older adults have demonstrated a reduced ability to recover balance after slipping, and therefore experience more falls.[49,52] Age is often accompanied by reduced muscle strength, slower reflexes, and poorer postural control, which can impair the ability to recover from an unexpected perturbation.[53] Similarly, reduced strength at the ankle, knee, and hip has been identified as a risk factor for falls among the elderly.[54] Physical activity has been associated with both increasing and decreasing fall risk.[55] Exercise can help older adults maintain the balance, strength, and coordination necessary to recover from a slip or trip perturbation. However, regular exercise exposes older adults to opportunities to slip or trip.[54,55] Vestibular dysfunction a common disorder associated with age, and can limit a person's ability to detect and react to the onset of a slip.[4] Vision impairment also tends to worsen with age, and reduced a person's ability to detect a fall hazard and implement balance recovery strategies.[4] Poor depth perception often accompanies impaired vision, and has been identified as a critical risk factor for falling among older adults.[56]

Various studies have investigated fall rates between younger and older adults. Rosenblatt and Grabiner (2012) found that older, healthy women fell at a higher rate than middle-aged women following a laboratory-induced trip.[36] Thelen, et al. (1997) found that older adults have a reduced ability to recover from a forward lean using a rapid step recovery.[57] Pavol, et al. (2002) compared recovery abilities between young and older adults after exposure to a laboratory-induced slip during a sit-to-stand motion. During this study, the older group experienced three times as many falls compared to the younger group, indicating a reduced ability to recover from a slip.[49] Lockhart found similar results in a study looking at slip severity and slip outcome during level walking. Healthy older adults experience faster and longer slips and fell more frequently than healthy young adults.[50] More research is needed to further investigate the role of aging combined with other risk factors, such as obesity, on balance recovery after a slip perturbation.

Summary & Purpose

Trends toward a more obese and older workforce in the United States threaten to exacerbate the already large problems of falls and fall-related injuries. Obesity and aging are associated with higher rate of falls, but the mechanisms and underlying factors contributing to these falls are still unclear. It is hypothesized that obesity and age increase the number of falls due to slipping. Therefore, the purpose of this study is to examine the effects of obesity and age on slip severity and balance recovery after a slip. In this study, four groups containing obese, non-obese, young, and older participants will be exposed to an unexpected slip perturbation. Any differences in slip severity or fall rate between groups can be used to identify aging and obesity as risk factors for experiencing slip-induced falls.

References

1. Lipscomb HJ, Glazner JE, Bondy J, Guarini K, Lezotte D. Injuries from slips and trips in construction. *Applied ergonomics*. May 2006;37(3):267-274.

2. Lin M-L, et al. *Injury Facts*. National Safety Council;2011.

3. Courtney TK, Sorock GS, Manning DP, Collins JW, Holbein-Jenny MA. Occupational slip, trip, and fall-related injuries--can the contribution of slipperiness be isolated? *Ergonomics*. Oct 20 2001;44(13):1118-1137.

4. Ambrose AF, Paul G, Hausdorff JM. Risk factors for falls among older adults: a review of the literature. *Maturitas*. May 2013;75(1):51-61.

5. Stephen P, Janocha, J. *Death on the job: fatal work injuries in 2011*. U.S. Bureau of Labor Statistics; August 2013 2013.

6. Bureau of Labor Statistics USDL. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011. 2012.

7. Yoon HY, Lockhart TE. Nonfatal occupational injuries associated with slips and falls in the United States. *International journal of industrial ergonomics*. Jan 1 2006;36(1):83-92.

8. Hanson JP, Redfern MS, Mazumdar M. Predicting slips and falls considering required and available friction. *Ergonomics*. Dec 1999;42(12):1619-1633.

9. Tsai Y-J, Powers, C.M. . The influence of footwear sole hardness on slip initiation in young adults. *J Forensic Sci*. 2008;53(4):884-888.

10. Menant JC, Steele JR, Menz HB, Munro BJ, Lord SR. Rapid gait termination: effects of age, walking surfaces and footwear characteristics. *Gait & posture*. Jul 2009;30(1):65-70.

11. Tencer AF, Koepsell, T.D., Wolf, M.E., Frankenfield, C.L., Buchner, D.M., Kukull, W.A., LaCroix, A.Z., Larson, E.B., Tautvydas, M. Biomechanical Properties of Shoes and Risk of Falls in Older Adults. *Journal of the American Geriatrics Society*. 2004;52:1840-1846.

12. Finkelstein EA, Chen, H., Malavika, P., Trogdon, J.G., Corso, P.S. The relationship between obesity and injuries among U.S. adults. *American Journal of Health Promotion*. 2007;21(5):460-468.

13. Madigan M, Rosenblatt NJ, Grabiner MD. Obesity as a Factor Contributing to Falls by Older Adults. *Current Obesity Reports*. 2014.

14. Redfern MS, Cham R, Gielo-Perczak K, et al. Biomechanics of slips. *Ergonomics*. Oct 20 2001;44(13):1138-1166.

15. England SA, Granata KP. The influence of gait speed on local dynamic stability of walking. *Gait & posture*. Feb 2007;25(2):172-178.

16. Brady RA, Pavol, M.J., Owings, T.M., Grabiner, M.D. . Foot displacement but not velocity predicts the outcome of a slip-induced fall in young subjects while walking. *Journal of biomechanics*. 2000;33:803-808.

17. Cooper RC, Prebeau-Menezes LM, Butcher MT, Bertram JE. Step length and required friction in walking. *Gait & posture*. May 2008;27(4):547-551.

18. Cham R, Redfern, M.S. Changes in gait when anticipating slippery floors. *Gait & posture*. 2001a.

19. Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. *Gait & posture*. Oct 2006;24(2):237-246.

20. Bakken GM, Hyde, A.S., et al. *Slips, Trips, Missteps, and their consequences*. 2nd ed. Tucson, AZ: Lawyers & Judges Pub. Co.; 2001.

21. Horak FB, Nashner, L.M. Central programming of postural movements: adaptation to altered support-surface configurations. *Journal of Neurophysiology*. 1986;55(6):1369-1381.

22. Maki BE, McIlroy, W.E. The role of limb movements in maintaining upright stance: the 'change-in-support' strategy. *Physical Therapy*. 1997;77:488-507.

23. Strandberg L, Lanshammar, H. . The dynamics of slipping accidents. *Journal of Occupational Accidents*. 1981;3:153-162.

24. Moyer BE, Redfern, M.S., Cham, R. Biomechanics of trailing leg response to slipping - Evidence of interlimb and intralimb coordination. *Gait & posture*. 2009;29:565-570.

25. Cham R, Redfern, M.S. Lower extremity corrective reactions to slip events. *Journal of biomechanics*. 2001;34:1439-1445.

26. Liu J, Lockhart TE. Age-related joint moment characteristics during normal gait and successful reactive-recovery from unexpected slip perturbations. *Gait & posture*. Oct 2009;30(3):276-281.

27. You JY, Chou, Y.L., Lin, C.J., Sun, F. C. . Effect of slip on movement of body center of mass relative to base of support. *Clinical Biomechanics*. 2001;16:167-173.

28. Pavol MJ, Owings, T.M., Foley, K.T., Grabiner, M.D. Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *Journal of Gerontology*. 2001;56A(7):M428-M437.

29. Yang F, Bhatt, T., Pai, Y.-C. Limits of recovery against slip-induced falls while walking. *Journal of biomechanics*. 2011;44:2607-2613.

30. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011. *Bureau of Labor Statistics*. 2012.

31. Flegal KM, Carroll MD, Kit BK, Ogden CL. Prevalence of obesity and trends in the distribution of body mass index among US adults, 1999-2010. *JAMA*. Feb 1 2012;307(5):491-497.

32. Ogden CL CM, Kit BK, Flegal KM. Prevalence of obesity and trends in the distribution of body mass index among US adults, 1999-2010. *JAMA*. 2012;307(5):491-497.

33. *Clnical Guidelines on the Identification, Evaluation, and Treatment of Overweight and Obesity in Adults*. U.S. Department of Health and Human Services;1998. 98-4083.

34. Fjeldstad C, Fjeldstad AS, Acree LS, Nickel KJ, Gardner AW. The influence of obesity on falls and quality of life. *Dynamic medicine : DM*. 2008;7:4.

35. Kouvonen A, Kivimaki M, Oksanen T, et al. Obesity and occupational injury: a prospective cohort study of 69,515 public sector employees. *PloS one*. 2013;8(10):e77178.

36. Rosenblatt NJ, Grabiner MD. Relationship between obesity and falls by middle-aged and older women. *Arch Phys Med Rehabil*. Apr 2012;93(4):718-722.

37. Matter KC, Sinclar, S.A., Hostetler, S.G., Xiang, H. A Comparison of the Characteristics of Injuries Between Obese and Non-obese Inpatients. *Obesity*. 2007;15(10):2384-2390.

38. Wearing SC, Hening, E.M., Byrne, N.M., Steele, J.R., Hills, A.P. The biomechanics of restricted movement in adult obesity. *Obesity Reviews*. 2006;7:13-24.

39. Hue O, Simoneau M, Marcotte J, et al. Body weight is a strong predictor of postural stability. *Gait & posture*. Jun 2007;26(1):32-38.

40. Wu X, Lockhart TE, Yeoh HT. Effects of obesity on slip-induced fall risks among young male adults. *Journal of biomechanics*. Apr 5 2012;45(6):1042-1047.

41. Teasdale N, Simoneau M, Corbeil P, Handrigan G, Tremblay A, Hue O. Obesity Alters Balance and Movement Control. *Current Obesity Reports*. 2013;2(3):235-240.

42. Lerner ZF, Board WJ, Browning RC. Effects of obesity on lower extremity muscle function during walking at two speeds. *Gait & posture*. Mar 2014;39(3):978-984.

43. Toossi M. Labor force projections to 2018: older workers staying more active. *Monthly Labor Review*. 2009:30-51.

44. Bureau of Labor Statistics, U.S. Department of Labor. Labor force participation projected to fall for people under age 55 and rise for older age groups. *The Editor's Desk* http://www.bls.gov/opub/ted/2014/ted_20140106.htm. Accessed June 18, 2014.

45. *Accident Facts*. Ithaca, IL: National Safety Council;1998.

46. Dunlop DD, Manheim LM, Sohn M-W, Liu X, Chang RW. Incidence of functional limitation in older adults: The impact of gender, race, and chronic conditions. *Archives of Physical Medicine and Rehabilitation*. 2002;83(7):964-971.

47. Luukinen H, Herala, M., Koski, K., Honkanen, R., Laippala, P., Kivelä, S.-L. Fracture Risk Associated with a Fall According to Type of Fall Among the Elderly. *Osteoporosis International*. 2000;11:631-634.

48. Lockhart TE. An integrated approach towards identifying age-related mechanisms of slip initiated falls. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*. Apr 2008;18(2):205-217.

49. Pavol MJ, Runtz, E.F., Edwards, B.J., Pai, Y.-C. Age influences the outcome of a slipping perturbation during initial but not repeated exposures. *Journal of Gerontology*. 2002;57A(8):M496-M503.

50. Lockhart TE, Woldstad JC, Smith JL. Effects of age-related gait changes on the biomechanics of slips and falls. *Ergonomics*. Oct 10 2003;46(12):1136-1160.

51. Hasselkus BR, et al. Aging and Postural Sway in Women. *Journal Of Gerontology*. 1975;30(6):661-667.

52. Lockhart TE, Smith, J.L., Woldstad, J.C. Effects of Aging on the Biomechanics of Slips and Falls. *Human Factors*. 2005;47(4):708-729.

53. Jensen JL, Brown, L.A., Woollacott, M.H. Compensatory Stepping: The Biomechanics of a Preferred Response Among Older Adults. *Experimental Aging Research*. 2001;27:361-376.

54. Myers AH, Young, Y., Langlois, J.A. Prevention of Falls in the Elderly. *Bone*. 1995;18(1):87S-101S.

55. O'Loughlin JL, Robitaille, Y., Boivin, J.F., Suissa, S. Incidence of and risk factors for falls and injurious falls among the community-dwelling elderly. *American journal of epidemiology*. 1993;137(3):342-354.

56. Salonen L, Kivela SL. Eye diseases and impaired vision as possible risk factors for recurrent falls in the aged: a systematic review. *Current gerontology and geriatrics research*. 2012;2012:271481.

57. Thelen DG, Wojcik, L.A., Schultz, A.B., Ashton-Miller, J.A., Alexander, N.B. Age differences in using a rapid step to regain balance during a forward fall. *The journals of gerontology*. 1997;52(1):8-13.

Chapter 3 – Obesity increases Fall Frequency after Slipping

Introduction

Falls and fall-related injuries are a significant occupational safety problem. In 2011, falls accounted for 553 occupational fatalities and 22% of injuries requiring days away from work.[1] These injuries can include sprains, strains, fractures, bruises, contusions, brain trauma, and even death.[2] Other consequences are less tangible, and can involve a loss of mobility, reduced confidence, and fear of falling.[3] Fall-related injuries are also an economic concern, with annual costs estimated to be a staggering $5.7 billion.[4] Slipping causes an estimated 40-50% of all fall-related injuries.[2] For instance, during the construction of the Denver International Airport between 1989 and 1994, slips caused 85% of same-level falls and 30% of falls to a lower level.[5]

The problem of slip-related falls in the workplace could be exacerbated by a high prevalence of obesity in the U.S. In the 1960s, only 13% of the U.S. population was considered obese (based upon body mass index).[6] In 2011-2012, 68.5% of the population was estimated to be overweight ($25 < \text{BMI} < 30$ kg/m^2) or obese (BMI ≥ 30 kg/m^2), and 34.9% was estimated to be obese.[7] Fjeldstad et al. (2008) reported a higher rate of falling among obese adults over 50.[8] Higher fall rates among those who are obese could be due to a variety of biomechanical and physiological characteristics, which include: lower muscle strength relative to body weight (which is related to mobility and overall physical capability)[9], increased inertia (which can impair balance recovery from perturbations involving initial angular acceleration[10]), reduced plantar sensitivity (which could alter balance[11]), and reduced stability during walking[12] (which is associated with increased fall risk[13]).

The problem of slip-related falls in the workplace could also be worsened by increased labor force participation rates among older adults. In 2002, 62% of adults aged 55-64 were working, while 68% of adults in this same age range are projected to be working 2022.[14] Older adults (albeit over 65 years of age) fall more frequently than young adults,[15] and these falls have been attributed to impaired vision, vertigo, poor postural stability, and reduced muscle strength.[16] Individuals who are obese and older would seem to be at a particularly elevated risk for falling due to the combined number of risk factors associated with obesity and aging. However, no biomechanical studies to our knowledge have investigated the combined effects of obesity and age on slips and falls.

Therefore, the purpose of this study was to investigate the effects of obesity and age on slip severity and fall frequency following an unexpected slip. Three hypotheses were formulated: (1) obese adults would experience more severe slips than non-obese adults; (2) obese adults would fall more frequently than non-obese adults after slipping; (3) an obesity × age interaction would exist by which the effects of obesity on slip severity and slip frequency would be larger among older adults than younger adults. Any differences in slip severity or fall frequency between these groups can be used to help identify workers at an increased risk of falling from a slip, and potentially guide subsequent investigations aimed at developing fall prevention strategies.

Methods

Seventy-two adults participated in the study, including 26 young (18-29 years) non-obese (BMI ≤ 24.9 kg/m^2); 25 young obese (BMI ≥ 29.1 kg/m^2); 10 older (50-66 years) non-obese (BMI ≤ 26.3 kg/m^2); and 11 older obese (BMI ≥ 30.06 kg/m^2) adults (Table 1). Participants were recruited from the university and local community using university announcements, community flyers, and newspaper advertisements. All participants were required to pass a medical questionnaire that assessed self-reported musculoskeletal or neurological disorders that could affect their gait or balance. Participants aged 65 and older, as well as one 60-year-old participant based upon responses to the medical questionnaire, were also required to pass a medical screening administered by a physician. This screening excluded participants with any neurological, cardiac, respiratory, ontological, or musculoskeletal disorders, and a minimum bone density of the femoral neck of 0.65 g/cm^2 as assessed by DXA (General Electric, Lunar Digital Prodigy Advance, Madison, WI). The university Institutional Review Board approved this study, and informed consent was obtained from all participants prior to participation.

Table 1. Participant demographic information (mean ± standard deviation)

		Gender		Age	BMI
	n	**Male**	**Female**	**(years)**	**(kg/m^2)**
Young Obese	25	11	14	21.3 ± 2.4	33.18 ± 3.02
Young Non-Obese	26	12	14	21.4 ± 2.1	21.98 ± 2.20
Older Obese	11	5	6	57.2 ± 5.6	33.53 ± 4.12
Older Non-Obese	10	5	5	58.9 ± 5.9	23.64 ± 2.07

Each participant completed one experimental session during which they were exposed to an unexpected slip while walking on a level walkway. The participant was asked to look straight ahead and walk at a comfortable, but purposeful, pace along a 10-meter walkway covered in vinyl tile. First, participants performed five to ten practice trials to adjust to the lab environment, and to establish a starting position so the dominant foot (preferred foot to kick a ball) naturally and consistently landed on a force platform integrated in the walkway. The participant was then informed that a slip or trip may or may not occur during any subsequent walk down the walkway. The participant was instructed that, if slipped or tripped, they should attempt to recover their balance and continue walking. All participants wore polyvinylchloride (PVC) -soled shoes to prevent any frictional differences between participants at the shoe-floor interface. To prevent impact with the floor in the event of an unsuccessful balance recovery, each participant wore a safety harness with a rope connecting the harness to a sliding track above the walkway. The rope was adjusted so that the participant's hands could not touch the floor and their knees would be approximately 6-inches from the floor when kneeling.

Figure 2. The experimental setup, showing a modified Helen-Hayes marker set, PVC-soled shoes, headphones, force plate, and safety harness. Photo by author, 2014.

To divert attention from walking and the possibility of a slip or trip, participants watched television (one positioned at each end of the walkway) and listened to the audio through wireless headphones while walking. For approximately 1-2 minutes between consecutive trials, participants stood at the end of the walkway, with their backs to the walkway, and watched the television until instructed by the investigator to turn around and begin the next trial (this allowed the investigators time to prepare for the next trial). The lights in the lab were dimmed throughout testing to reduce any glare created by the slip contaminant.

After a minimum of ten acceptable walking trials (with proper foot placement onto the force plate and walking speed not fluctuating by more than ± 0.1 m/s between trials), a foam paint roller was used to apply a thin layer of vegetable oil (50 mL) to the entire surface of the force platform (0.9 m × 0.9 m) while the participant faced away from the walkway. The trial then continued using the same procedure as earlier trials. The slip occurred when the dominant foot contacted the contaminated surface. All participants were successfully slipped on the first attempt.

During each trial, the three-dimensional positions of 28 reflective markers were sampled at 100 Hz using a six-camera Vicon motion analysis system (Vicon Motion Systems, Centennial, CO) and low-pass filtered at 7 Hz (second-order, zero-phase-lag Butterworth filter). Reflective markers were placed at anatomical landmarks based on a modified Helen Hayes marker set. Ground reaction forces under the slipping foot and the force applied to the harness were sampled at 1000 Hz using a 6-degree of freedom force platform (Bertec Corporation, Columbus, OH) and uniaxial load cell (Cooper Instruments and Systems, Warrenton, VA). Both were low-pass filtered at 20 Hz (second-order, zero-phase-lag Butterworth filter).

Five dependent variables were extracted using Matlab 2013a (The Mathworks Inc., Natick, MA) for each slip trial: gait speed, step length, slip duration, slip distance, peak slip velocity, and average slip velocity. Gait speed during the slip trial was calculated as the forward speed of a sacrum marker for 2-3 steps preceding slip onset.[17] Slip severity parameters (slip distance, slip duration, peak slip velocity, and average slip velocity)[17] were calculated with respect to two main events: slip onset and slip end.[17-19] Slip onset was defined as heel contact onto the contaminated surface using data collected from the force plate.[17] The slip end was defined as the time when either: (1) the slip distance exceeded the length of the force plate, (2) the heel came to a stop, or (3) the heel displaced vertically from the force plate.[17,20] Slip distance was calculated as the total distance traveled from slip onset to slip end; slip duration was calculated as the time from slip onset to slip end. Peak slip velocity was calculated as the maximum velocity of the heel marker during the slip.[17] Velocity information was extracted from the marker position data using a finite difference algorithm.

Slip outcome was determined using data collected from the harness load cell. Slip outcomes were classified as: (1) *recovery*: peak harness load < 30% BW and integrated harness load < 8% body weight × second; (2) *fall*: peak harness load ≥ 50% body weight (BW) or a fall is unambiguously evident based on visual inspection; (3) trials not classified as fall or recovery were determined to be *harness-assisted*.[17,21] Slip severity parameters were analyzed for all slips classified as a fall or recovery. Further analysis was not performed on harness-assisted trials, since there is no way to determine what the slip outcome would have been without the presence of the harness.

Gait speed and step length were analyzed using a two-way analysis of variance with BMI group, age group, and their interaction. The interaction was not statistically significant, and was subsequently removed. Slip severity measures (slip duration, slip distance, peak slip velocity, average slip velocity) were analyzed using a three-way analysis of covariance with independent variables of BMI group, age group, and gender, with gait speed as a covariate. All three-way and two-way interaction effects were initially included in the analysis. Iterative backwards elimination then removed non-significant three-way and two-way interactions until the final model included only main effects and significant interactions. Following this procedure, no interactions remained for any of the dependent variables. Slip outcome was analyzed using a logistic regression model with the independent variables of BMI group, age group, gender, and gait speed. An age group × BMI group was initially included, but subsequently removed because it was not statistically significant. Statistical analyses were performed using JMP 10 (SAS Institute Inc., Cary, NC) with a significance level of $p \geq 0.05$.

Results

One of the four slip severity measures was affected by BMI group (Table 2). Slip duration (p=0.974), slip distance (p=0.121), and peak slip velocity (p=0.065) were not affected by obesity, but average slip velocity was 8.25% higher (p=0.022) among obese participants. Age group did not affect slip severity measures, including slip duration (p=0.112), slip distance (p=0.933), peak slip velocity (p=0.591), and average slip velocity (p=0.543; Table 2). Gait speed affected three of four slip severity measures. Gait speed did not affect slip duration (p=0.1478), but slip distance (p=0.005), peak slip velocity (p<0.001), and average slip velocity (p<0.001) increased as gait speed increased. However, gait speed and step length were not affected by BMI group (speed p=0.486, step length p=0.886) or age group (speed p=0.245, step length p=0.593; Table 2).

Table 2. Gait and slip severity measures (mean ± standard deviation)

	Gait Measures		Slip Severity Measures			
	Gait Speed (m/s)	**Step Length (m)**	**Slip Duration (s)**	**Slip Distance (cm)**	**Peak Slip Velocity (m/s)**	**Average Slip Velocity (m/s)**
Obese	1.25 ± 0.14	0.70 ± 0.07	0.42 ± 0.27	42.1 ± 27.2	1.89 ± 0.98	1.05 ± 0.59*
Non-obese	1.31 ± 0.17	0.69 ± 0.13	0.38 ± 0.24	38.4 ± 23.9	1.70 ± 0.89	0.97 ± 0.61*
Older	1.32 ± 0.19	0.70 ± 0.08	0.32 ± 0.10	42.2 ± 25.5	1.84 ± 0.90	1.16 ± 0.66
Young	1.27 ± 0.14	0.71 ± 0.06	0.36 ± 0.12	40.2 ± 25.3	1.81 ± 0.93	0.97 ± 0.56
Male	1.29 ± 0.16	0.73 ± 0.06	0.31 ± 0.09	34.2 ± 23.4	1.67 ± 0.90	0.96 ± 0.60
Female	1.27 ± 0.16	0.69 ± 0.07	0.38 ± 0.12	46.5 ± 25.6	1.95 ± 0.91	1.08 ± 0.58

* Significantly different between BMI groups

Falls were more frequent among obese participants (p=0.005; Figure 3). One-third, or 33.3%, of obese participants fell after slipping compared to 8.6% of non-obese participants. The odds ratio for BMI group indicated that obese participants were 8.24 [95% C.I.: 1.81, 57.10] times more likely to fall than non-obese participants, when adjusting for age group, gender, and gait speed. Furthermore, the odds ratio for BMI, when including BMI and age in the logistic regression as continuous variables was 1.15 [95% C.I.: 1.03, 1.31] for a unit increase in BMI. Slip outcome was not affected by age group (p=0.937) or gender (p=0.399; Table 3). However, a fall was more likely as gait speed increased (p=0.003), and the odds ratio was 1430 [95% C.I.: 10.4, 554853] for a unit (i.e. 1 m/s) increase in gait speed when adjusted for BMI group, age group, and gender.

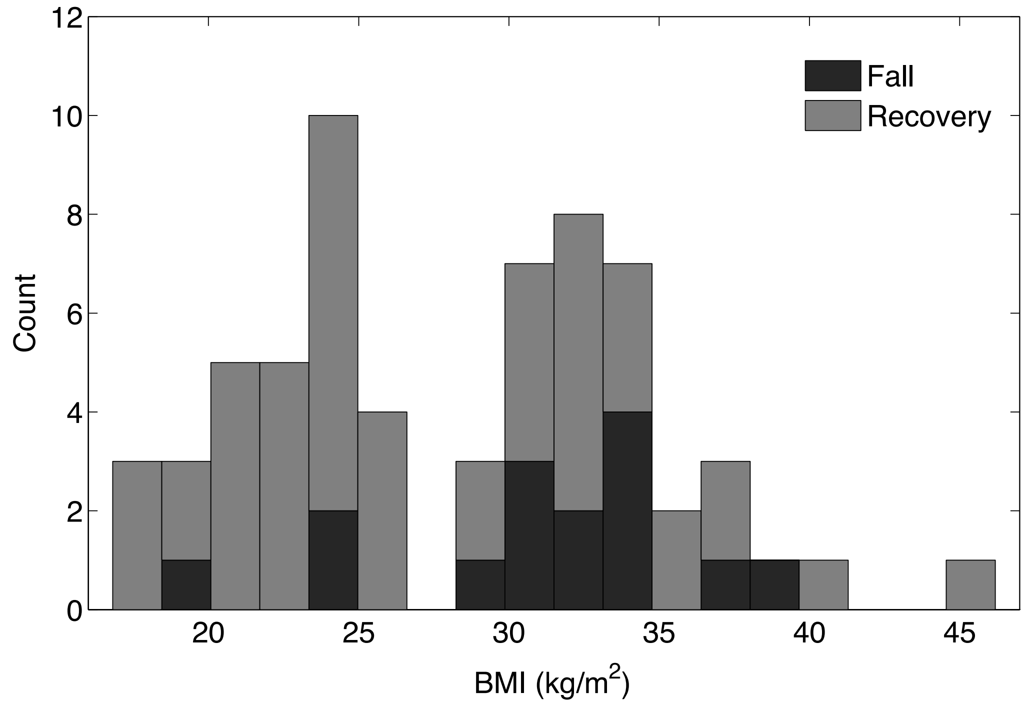

Figure 3. The distribution of falls and recoveries across BMI shows a higher number of falls among the obese group.

Table 3. Slip outcomes among groups

	Fall	Recovery	Harness-Assisted	Total
Total	15	48	9	72
Obese	12	21	3	36
Non-obese	3	27	6	36
Older	5	12	4	21
Young	10	36	5	51
Male	5	24	4	33
Female	10	24	5	39

Although there were no slip severity thresholds that separated all falls from all recoveries, participants who fell tended to experience more severe slips (Figure 4). More falls occurred with longer slip distances, but the slip distance for some recovery trials surpassed slip distances resulting in falls (Figure 5). The majority of falls occurred at peak slip velocities at or above 2 m/s, average slip velocities over 1.0 m/s, distances beyond 50 cm, and durations of more than 0.3 seconds. Thresholds for slip distance, slip duration, and peak slip velocity were found to correctly estimate the most falls from the most recoveries. A slip distance of 56.5 cm separated 85.4% of recoveries from 86.7% of falls, a slip duration of 0.349s separated 54.2% of recoveries from 86.7% of falls, and a peak slip velocity of 2.565 m/s separated 91.7% of recoveries from 80.0% of falls (Figure 4). A threshold was not established for average slip velocity, since a practical application is unclear.

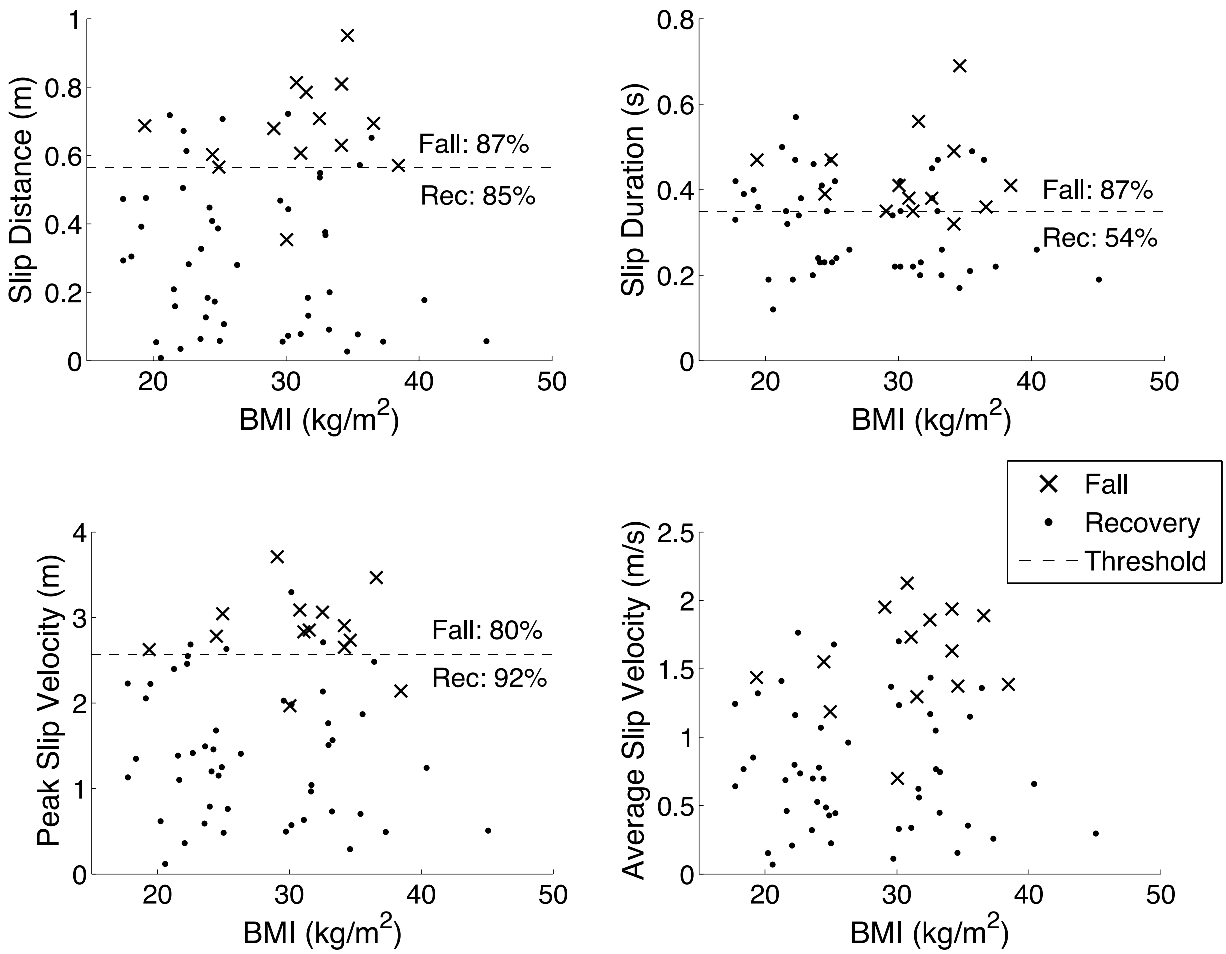

Figure 4. Slip severity parameters from all slip trials as a function of subject BMI. Most falls occurred among the obese group, and were associated with more severe slips. Slip severity threshold lines separate most falls from most recoveries.

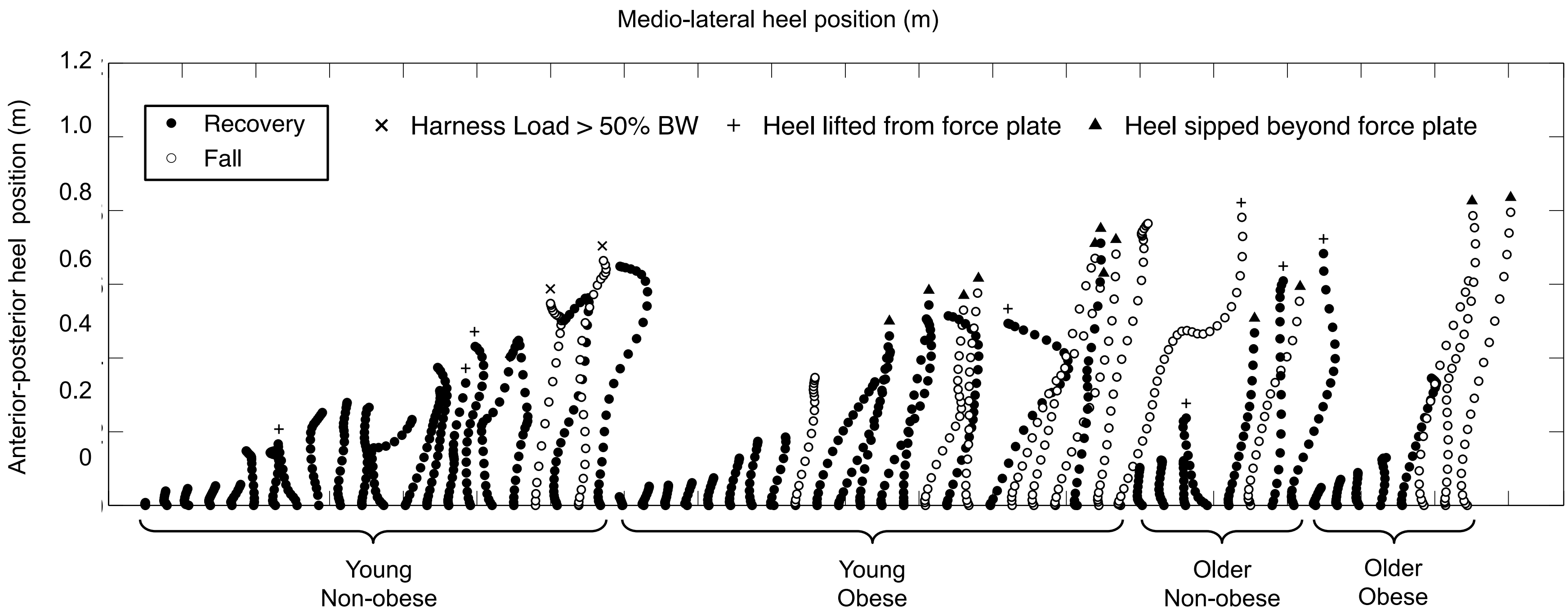

Figure 5. Sliding heel trajectories for all slips classified as recoveries or falls, organized based on slip distance and age/BMI group. Each data point represents the sliding heel position from slip onset to slip end, separated by 20ms intervals. Slips ended when the sliding heel came to a stop, unless otherwise indicated.

Discussion

The purpose of this study was to investigate the effects of obesity and age on slip severity and fall frequency following an unexpected slip. The first hypothesis was that obese adults would experience more severe slips than non-obese adults. This hypothesis was accepted because average slip velocity was higher among obese adults (and a post-hoc power analysis indicated peak slip velocity would have be statistically significant with only four more participants added to each group, assuming the same standard errors and structural results as the current sample). The second hypothesis was that obese adults would fall more frequently than non-obese adults after slipping. This hypothesis was accepted because obese adults were 8.24 times more likely to fall after slipping compared to non-obese adults. The third hypothesis was that an obesity × age interaction would exist whereby the effects of obesity on slip severity and slip frequency would be larger among older adults than young adults. This hypothesis was rejected because no obesity group × age group interactions existed for any slip severity measures or slip outcome. Results from this study suggest that a higher rate of falling from slipping may contribute to the higher rate of falls among obese individuals that have been reported elsewhere.

Results from this study indicated that obese individuals are at a higher risk of falling from an unexpected slip than non-obese individuals. To our knowledge, no other studies have investigated the effects of obesity on slip severity or slip outcome. Rosenblatt and Grabiner (2012) investigated the relationship between obesity and falls among middle-aged and older women. A retrospective analysis of self-reported falls and stumbles over the past year showed similar fall rates among obese and non-obese women. However, following laboratory-induced trips among women over 55 years of age, obese women fell at a 21.2% higher rate (although the results were not statistically significant to p=0.05).[22] Although slips typically involve a backward loss of balance and trips typically involve a forward loss of balance, these studies provide evidence for a reduced ability for obese individuals to recover from a large postural perturbation while walking.

Certain physiological and biomechanical factors associated with obesity may influence balance recovery. Higher weight and reduced lower extremity muscle strengths (relative to body weight) may impair balance recovery among those who are obese, as higher body mass would require higher joint torques to return the body to equilibrium.[23] Additionally, added body weight has been found to increase COP movement during quiet standing, which may be related to balance recovery.[24] Gait biomechanics may also predispose obese persons to slipping and falling. Lai et al. (2008) found that obese participants walked slower, and with shorter strides than non-obese participants.[25] Other researcher have linked slower walking speed to decreased stability during slipping.[26] These conditions associated with obesity may have led to a decreased ability to recover balance from a slip.

Neither slip severity nor fall outcome differed between young and older adults during the present study. Lockhart et al. (2003) found that, when exposed to an unexpected slip while walking, older adults (over 65 years old) experienced more severe (i.e. faster and farther) slips than their younger counterparts. Older adults experienced slip velocities (averaged between slip start and peak slip velocity) of 0.76 m/s, compared to 0.44 m/s among the younger participants. Additionally, older adults experienced slip distances (measured between slip start and peak slip velocity) of 11.8 cm, compared to 4.98 cm among younger participants. A direct comparison between these measurements and those from the current study are not possible due to differences in how they were calculated. Lockhart et al. also reported that older adults fell at a higher rate than younger adults, with falls occurring if the whole body COM velocity exceeded the sliding heel velocity or a fall was evident based on visual inspection.[27] Discrepancies in slip outcome results between Lockhart et al. and the current study could be attributed to at least three experimental differences. First, the older participant group used by Lockhart et al. had a mean age of 75.5 years, whereas the mean age for this study was 58.0 years. Age differences in slip severity and slip outcome may not be apparent until after the age of 58. Second, the methods to determine fall outcome differed between studies. Third, differences in materials for the shoe, floor, and contaminant, could have influenced friction at the shoe-floor interface, slip severity, and as a result, slip outcome.

Slip severity was related to slip outcome in that, in general, more falls occurred from more severe slips (i.e. faster, farther, and longer in duration; Figure 4). Other researchers have reported thresholds of slip severity that largely separated falls and recoveries. For example, slip distance has been shown to separate slip-induced falls from recoveries. In a study on slips induced during level walking, Strandberg and Lanshammar (1981) observed that “near-falls”, or slips requiring large compensatory swing-leg and arm motions, had sliding distances of about 10 cm.[27] Brady et al. (2000) exposed participants to unexpected slips during barefoot level walking, and found that all falls occurred at slip distances farther than 27 cm.[17] In the current study, falls occurred for distances as short as 35.4 cm, and a threshold of 56.5 cm separated most falls from most recoveries. The slip distance of 56.5 cm that separated most recoveries from most falls could be used to design fall resistant floors. Floors with high friction markings or boundaries spaced no father than 56.5 cm apart could potentially prevent slip-induced falls. Slip velocity has also been linked to slip outcome. Strandberg (1983) found slip-recoveries to be associated with peak slipping foot velocities of about 0.3-0.5 m/s, and slip-falls exhibiting peak velocities greater than walking speed (1-2 m/s).[28] During the current study, falls occurred at peak slip velocities greater than 1.96 m/s and average slip velocities greater than 0.85 m/s. A peak slip velocity threshold of 2.57 m/s correctly estimated 91.7% of recoveries and 80% of falls. Discrepancies in slip severity parameters between studies can be attributed to differences in the experimental setups. Strandberg (1983) induced slips by applying a soap patch to the floor, and participants were slipped multiple times using different shoes. Brady et al. (2000) induced slips using vinyl tile covered in a water-detergent mixture while walking barefoot at a self-selected speed.[17] These differences in the experimental setups (shoes, floor surface, contaminant) induce changes in frictional properties between the shoe and floor. Additionally, when more than one slip is induced in a single participant, more cautious gait changes can be adopted for subsequent trials.[29] The slip severity thresholds that separated most recoveries from most falls in the current study did not appear to be influenced by BMI (Figure 4).

Another factor influencing fall outcome was gait speed, as faster walkers experienced more severe slips and fell more frequently. Researchers have reported inconsistent results when examining the effects of gait speed on slip outcome. Espy et al. (2010) found that faster gait reduced fall risk when participants were slipped during walking.[30] Bhatt and Pai (2005) induced slips for healthy adults at three self-selected gait speeds: slow, normal, and fast. Results from this study indicated that stability improved with increased gait speed.[26] Conversely, Hu and Qu (2013) induced slips among participants using a removable vinyl sheet covered in a vinyl-detergent mixture, and found no differences in walking speed between falls and successful recoveries. Brady et al. (2000) also found no effect of gait speed on slip outcome when participants were exposed to an unexpected slip.[19] For studies by Hu and Chu and Brady, participants walked at a self-selected gait speed.

Several limitations were present in this study. First, participants were warned of a possible slip, so anticipation effects may have existed, such as cautious gait adaptations and heightened alertness.[31-34] Second, as with any cross-sectional study, differences between groups other than BMI and age could have contributed to our results (e.g. physical activity level, body composition). Third, determining the slip end added uncertainty to the data. Several participants slipped past the force plate, and it is unclear as to how far these participants would have slipped had the force plate not existed.

In conclusion, obese participants experienced faster slips and fell more frequently than non-obese participants. Based on these results, obesity appears to be a significant risk factor for experiencing slip-induced falls. Age did not appear to increase fall risk after slipping. Results from this study suggest that the epidemiological data reporting higher fall rates among the obese may be due, in part, to a greater rate of falling after slipping while walking.

References

1. Stephen P, Janocha, J. *Death on the job: fatal work injuries in 2011*. U.S. Bureau of Labor Statistics; August 2013 2013.

2. Courtney TK, Sorock GS, Manning DP, Collins JW, Holbein-Jenny MA. Occupational slip, trip, and fall-related injuries--can the contribution of slipperiness be isolated? *Ergonomics*. Oct 20 2001;44(13):1118-1137.

3. Ambrose AF, Paul G, Hausdorff JM. Risk factors for falls among older adults: a review of the literature. *Maturitas*. May 2013;75(1):51-61.

4. Yoon HY, Lockhart TE. Nonfatal occupational injuries associated with slips and falls in the United States. *International journal of industrial ergonomics*. Jan 1 2006;36(1):83-92.

5. Lipscomb HJ, Glazner JE, Bondy J, Guarini K, Lezotte D. Injuries from slips and trips in construction. *Applied ergonomics*. May 2006;37(3):267-274.

6. Wang Y, Beydoun MA. The obesity epidemic in the United States--gender, age, socioeconomic, racial/ethnic, and geographic characteristics: a systematic review and meta-regression analysis. *Epidemiologic reviews*. 2007;29:6-28.

7. Ogden CL, Carroll MD, Kit BK, Flegal KM. Prevalence of childhood and adult obesity in the United States, 2011-2012. *JAMA*. Feb 26 2014;311(8):806-814.

8. Fjeldstad C, Fjeldstad AS, Acree LS, Nickel KJ, Gardner AW. The influence of obesity on falls and quality of life. *Dynamic medicine : DM*. 2008;7:4.

9. Lerner ZF, Board WJ, Browning RC. Effects of obesity on lower extremity muscle function during walking at two speeds. *Gait & posture*. Mar 2014;39(3):978-984.

10. Matrangola SL, Madigan ML. The effects of obesity on balance recovery using an ankle strategy. *Human movement science*. Jun 2011;30(3):584-595.

11. Teasdale N, Simoneau M, Corbeil P, Handrigan G, Tremblay A, Hue O. Obesity Alters Balance and Movement Control. *Current Obesity Reports*. 2013;2(3):235-240.

12. Colne P, Frelut ML, Peres G, Thoumie P. Postural control in obese adolescents assessed by limits of stability and gait initiation. *Gait & posture*. Jul 2008;28(1):164-169.

13. Liu J, Zhang X, Lockhart TE. Fall risk assessments based on postural and dynamic stability using inertial measurement unit. *Safety and health at work*. Sep 2012;3(3):192-198.

14. Bureau of Labor Statistics, U.S. Department of Labor. Labor force participation projected to fall for people under age 55 and rise for older age groups. *The Editor's Desk* http://www.bls.gov/opub/ted/2014/ted_20140106.htm. Accessed June 18, 2014.

15. Tromp AM, Pluijm SM, Smit JH, Deeg DJ, Bouter LM, Lips P. Fall-risk screening test: a prospective study on predictors for falls in community-dwelling elderly. *Journal of clinical epidemiology*. 2001 2001;54(8).

16. Tuunainen E, Rasku J, Jantti P, Pyykko I. Risk factors of falls in community dwelling active elderly. *Auris, nasus, larynx*. Feb 2014;41(1):10-16.

17. Brady RA, Pavol, M.J., Owings, T.M., Grabiner, M.D. . Foot displacement but not velocity predicts the outcome of a slip-induced fall in young subjects while walking. *Journal of biomechanics*. 2000;33:803-808.

18. Strandberg L, Lanshammar, H. . The dynamics of slipping accidents. *Journal of Occupational Accidents*. 1981;3:153-162.

19. Redfern MS, Cham R, Gielo-Perczak K, et al. Biomechanics of slips. *Ergonomics*. Oct 20 2001;44(13):1138-1166.

20. Cham R, Redfern, M.S. Lower extremity corrective reactions to slip events. *Journal of biomechanics*. 2001;34:1439-1445.

21. Yang F, Pai YC. Automatic recognition of falls in gait-slip training: Harness load cell based criteria. *Journal of biomechanics*. Aug 11 2011;44(12):2243-2249.

22. Rosenblatt NJ, Grabiner MD. Relationship between obesity and falls by middle-aged and older women. *Arch Phys Med Rehabil*. Apr 2012;93(4):718-722.

23. Madigan M, Rosenblatt NJ, Grabiner MD. Obesity as a Factor Contributing to Falls by Older Adults. *Current Obesity Reports*. 2014.

24. Costello KE, Matrangola, S.L., Madigan, M.L. Independent effects of adding weight and inertia on balance during quiet standing. *Biomedical Engineering Online*. 2012;11(20).

25. Lai PP, Leung AK, Li AN, Zhang M. Three-dimensional gait analysis of obese adults. *Clin Biomech (Bristol, Avon)*. 2008;23 Suppl 1:S2-6.

26. Bhatt T, Wening JD, Pai YC. Influence of gait speed on stability: recovery from anterior slips and compensatory stepping. *Gait & posture*. Feb 2005;21(2):146-156.

27. Lockhart TE, Woldstad JC, Smith JL. Effects of age-related gait changes on the biomechanics of slips and falls. *Ergonomics*. Oct 10 2003;46(12):1136-1160.

28. Strandberg L. On accident analysis and slip-resistance measurement. *Ergonomics*. Jan 1983;26(1):11-32.

29. Beringer DN, Nussbaum MA, Madigan ML. Temporal changes in the required shoe-floor friction when walking following an induced slip. *PloS one*. 2014;9(5):e96525.

30. Espy DD, Yang F, Bhatt T, Pai YC. Independent influence of gait speed and step length on stability and fall risk. *Gait & posture*. Jul 2010;32(3):378-382.

31. Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. *Gait & posture*. Oct 2006;24(2):237-246.

32. Cham R, Redfern, M.S. Changes in gait when anticipating slippery floors. *Gait & posture*. 2001a.

33. Horak FB, Nashner, L.M. Central programming of postural movements: adaptation to altered support-surface configurations. *Journal of Neurophysiology*. 1986;55(6):1369-1381.

34. Beckley DJ, Bloem, B.R., Remler, M.P., Roos, R.A., Van Dijk, J.G. Long latency postural responses are functionally modified by cognitive set. *Electroencephalography and clinical neurophysiology*. 1991;81(5):353-358.