AN EXPLORATORY STUDY INVESTIGATING THE TIME DURATION OF SLIP-INDUCED CHANGES IN GAIT

Danielle Nicole Beringer

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

Masters of Science
In
Biomedical Engineering

Michael L. Madigan
Maury A. Nussbaum
Christopher Franck

May 6, 2013
Blacksburg, VA

Keywords: Biomechanics, Slips and falls, Gait adaptations, RCOF

AN EXPLORATORY STUDY INVESTIGATING THE TIME DURATION OF SLIP-INDUCED CHANGES IN GAIT

Danielle Nicole Beringer

ABSTRACT

The biomechanics of slips are commonly studied in laboratory settings in an effort to improve the understanding of slip mechanisms for the advancement of slip and fall prevention strategies and risk assessment methods. Prior studies have shown changes in gait after slipping, and these changes can reduce the external validity of experimental results. As such, most researchers only slip participants one time. The ability to slip participants more than once, after allowing gait to return to a natural baseline, would improve the experimental efficiency of these studies. Therefore, the goal of this study was to determine the time duration of slip-induced changes in gait. The required coefficient of friction (RCOF), a parameter highly predictive of risk of slipping, was measured on thirty-one young male adults during level gait on three separate days before slipping, immediately (<10 minutes) after slipping, and either one, two, four, or six weeks later. On average, the RCOF decreased 12% from its baseline value (0.20) after slipping, indicating the adoption of a protective gait with a decreased risk of slipping. The RCOF data trended toward baseline values 4-6 weeks after the slip experience, but remained statistically different from baseline. This indicates that the slip-induced gait alterations have long-lasting effects, enduring up to six weeks after the slip experience.

ACKNOWLEDGEMENTS

First I would like to recognize my advisor, Dr. Madigan. Thank you for sparking my interest in musculoskeletal biomechanics during my undergraduate studies, for giving me the opportunity to become involved in this research project on slip biomechanics, and for your unwavering support and guidance throughout the past two years. This would not have been possible without you.

I would also like to thank Dr. Nussbaum and Dr. Franck for serving as members of my committee, as well as Sam Lesko for your contributions to the development of this study.

Next, I would like to recognize Sara Matrangola for acting as my mentor throughout the past two years. Thank you for teaching me how to use the lab equipment and process data, as well as helping me plan and run the data collection sessions. Also, thank you for always knowing how to fix all of the little technical issues that arose. This project would not have been possible without your guidance.

I would also like to acknowledge the collaborators in the Laboratory for Interdisciplinary Statistical Analysis for their contribution to this study.

Thank you Tina, Hoda, Emily, and Courtney for your company in the lab, assisting with my testing sessions, and putting up with the nature sounds that were constantly playing in the background. These two years would not have been the same without you.

Finally, I would like to thank all of the undergraduate students who assisted with preliminary testing and data collection. Thank you Katie, John, Matt, Kevin, Kaitlyn, Jaclyn, Tyler, and Derek for your contribution to the study. Thank you John especially for completing the ongoing data collection as a continuation of this study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 – OVERVIEW

Falls are a significant source of injuries and fatalities in the United States, with a large portion resulting from slips. The biomechanics of slips are commonly studied in laboratory settings in an effort to improve the understanding of the intrinsic factors contributing to slips and falls. Advancements in the understanding of slip mechanisms could aid in targeting effective slip and fall prevention strategies and improve risk assessment methods. One challenge in this research area has been the ability to reproduce natural slips in experimental settings. Previous studies have demonstrated that both awareness of a slippery environment and prior slip experience alter an individual's gait. As such, most researchers only slip participants once in this type of experiment. A better understanding of slip-induced gait alterations could allow participants to be slipped more than once after an appropriate delay between slips to allow gait to return to baseline. The ability to slip participants more than once without compromising external validity could improve statistical power of an experiment through the use of a within-subject experimental design, and reduce the number of required participants potentially saving researchers time and money in recruitment costs.

This thesis summarizes the research performed on this topic as part of a Master's degree program. Chapter 2 is a literature review summarizing the intrinsic and extrinsic factors affecting the risk of slipping, and the changes in gait observed in participants with both awareness and experience of a slip. Chapter 3 is a self-contained manuscript documenting this research project that will be submitted for publication. This research project examines the time duration of slip-induced gait changes to better understand their implications for experimental design in this area of research.

CHAPTER 2 – INTRODUCTION

Societal Impact of Falls

Falls are a significant source of injuries and fatalities in the United States. In 2005, there were more than 8.7 million emergency department visits made to U.S. hospitals due to fall-related injuries, making up 20% of all injury visits.[1] Fall-related injuries vary significantly in severity, including minor injuries, like bruising, lacerations, strains, and sprains[2], disabling injuries, such as fractures and dislocations, and fatal injuries commonly involving head or neck trauma and damage to internal organs.[3] According to the National Safety Council, falls are the second-leading cause of unintentional death in homes and communities, resulting in more than 25,000 fatalities in 2009.[4] Falls have been targeted as a serious risk among two primary groups: older adults[5, 6] and workers in occupational settings.[7-10]

Occupational falls are the third leading cause of injury across all industries in the United States[10] and accounted for 15% of all fatal occupational injuries in 2011.[11] Over 330,000 non-fatal fall-related injuries requiring one or more days away from work were reported to the U.S. Bureau of Labor Statistics in 1996, and an additional 60,000 injuries related to slipping, tripping, or loss of balance without a resulting fall were also reported.[3] Claims for occupational fall-related injuries make up about 25% of all worker's compensation costs in the United States, estimated to total more than $6 billion annually.[3] Construction and manufacturing are the two most affected industries, responsible for about 50% and 10% of all fatal occupational falls, respectively.[9]

Older adults are particularly susceptible to falls and resulting injuries. The risk of falling increases with age, often due to weakness, unsteady gait, dizziness, a gradual degradation of vision, balance, and agility, and medication side effects.[5, 6, 12] In addition to the high incidence of falls, this population is also particularly susceptible to injury due to age-related physiological changes and clinical diseases, such as osteoporosis.[12] It is estimated that 30% of older adults experience a fall each year, and 20-30% of those who fall will sustain an injury.[5] Because of the increased susceptibility of older adults to injury, falls are more likely to result in fractures, which are a significant source of morbidity and mortality in this population.[2, 12, 13] Falls are responsible for 70% of all accidental deaths in adults over the age of 75.[6] The cost of health care associated with falls in older adults is exorbitant, largely due to the high rate of fatality, resulting disabling conditions, and extended hospital stays.[13] In the United States this cost was in excess of $8 billion in 2004, and is projected to increase as the population of older adults and health care costs continue to rise.[14]

The widespread problem of falls in the United States, and the magnitude of associated medical costs, highlight the importance of research into the mechanisms and prevention of falls.[14]

Slipping as a Fall Mechanism

Slipping events are responsible for the loss of balance that leads to a large proportion of falls.[3, 15-17] In Sweden, the ISA reported that slipping was the cause of 55% of same level falls and 23% of falls to a lower level in 1988.[3] The U.S. National Health

Interview Survey determined that 64% of all occupational falls resulting in injury were due to slipping, tripping, or stumbling.[3]

A slip, as defined by Grönqvist (1999), is 'a sudden loss of grip, often in the presence of liquid or solid contaminants and resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity'.[18] The causes of slips are complex, involving the interaction of several factors, both extrinsic (environmental factors) and intrinsic (human factors).[17, 19-21]

Extrinsic Factors Associated with Slip

The frictional properties of the interface between the shoe and floor are the primary environmental determinants of a slipping event.[19, 21] The static friction at the interface is an important predictor of slip initiation and the dynamic friction is relevant to slip propagation and recovery, characterized by the static and dynamic coefficients of friction (COF) respectively.[21, 22] The individual properties of both the shoe sole and the floor surface impact the available friction at the interface. Specifically, the geometry of the shoe's tread, inclination angle of the floor, and material, hardness, and roughness of the shoe's sole and floor surface are each important factors.[15, 19, 21]

The presence of contaminants on the floor surface also has a significant effect on the characteristics of the shoe-floor interface. Contaminants typically decrease the available friction, elevating the risk of slipping. The effect of a contaminant varies based on its viscosity, the depth of the film, and its interaction with both the floor and shoe surfaces.[15, 19-21] Additional environmental factors include quality of lighting and warning signs, which could affect an individuals awareness of a slippery surface.[19, 21]

Intrinsic Factors Associated with Slip

Although extrinsic factors alone can create an environment with a high risk of slipping, an individual's ability to adapt to the situation, governed by intrinsic factors, ultimately determines whether a slip event is initiated or prevented.[19] Several physiological and psychological factors affecting an individual's risk of slipping have been identified including: visual, vestibular, and proprioceptive systems; neuromuscular control; information processing; perception of slipperiness; and prior slip experience.[15, 19-21] Combined, these factors form a set of 'tools' necessary to react to a slippery environment and perform one of several slip prevention or recovery strategies. Deterioration or lack of any of these factors could inhibit an individual's ability to adapt to a slippery environment, leading to an increased risk of slipping and falling.[17] Additionally, multi-tasking and drug or alcohol use can impede an individual's ability to react and adapt to a slippery surface.[21]

The initiation and propagation of slip events are also largely affected by a second category of intrinsic biomechanical factors.[15, 17, 19-21] These factors quantitatively describe how the physiological and psychological 'tools' are utilized during walking and after perception of slip risk to prevent a slip, or after slip initiation to recover balance after a slip.[17] The biomechanical factors associated with slipping include postural control and kinetic and kinematic gait parameters.[15, 17, 21, 23, 24]

Postural control is an important biomechanical aspect of slip recovery.[17, 21, 23] When a slip is experienced, the body's center of mass is perturbed from its controlled trajectory, often moving beyond the bounds of the base of support, resulting in the loss of balance. Recovery from this type of perturbation requires detecting the perturbation and actively adjusting posture to restore the COM's position over the base of support.[21, 23] Measures of static and dynamic postural stability have been investigated as predictors of the ability to successfully detect and recovery from slip perturbations.[23]

Kinematic and kinetic gait parameters are also key factors effecting risk of slipping. A decreased foot-floor angle or angle of the shank to vertical at heel contact decreases the shear force at impact, and as a result less friction is demanded of the environment to support walking, reducing the risk of slipping.[24, 25] Similarly, decreased walking speed and shorter steps also reduce the risk of slipping.[21] These kinematic parameters influence the risk of slipping by affecting the kinetic parameters associated with slipping. Kinetic parameters correlated with risk of slipping include loading rate, peak shear force, and required coefficient of friction (RCOF), which directly affect the amount of friction required to support walking.[24-26] Awareness of a potential slip risk or perception of low-friction conditions induces adaptations in these factors that result in a protective gait, decreasing the risk of slipping.[21]

Required Coefficient of Friction

The required coefficient of friction (RCOF) is one of the most critical gait parameters in predicting risk of slipping.[26] The RCOF is the minimum COF necessary at the foot-floor interface to support walking, and has been compared to the environmentally available COF as an assessment of slip probability.[17, 19, 26] To determine the RCOF, the instantaneous COF is calculated as the ratio of the shear to normal ground reaction force during stance. The RCOF is typically considered to be the local maximum of the instantaneous COF curve at ~20% of the stance phase of gait during weight acceptance, identified as ‘Peak 3’ in Figure 1.[26] Another local maximum occurs at ~90% of the stance phase of gait during push-off, but this peak is thought to be less risky for a slip-induced fall.[26]

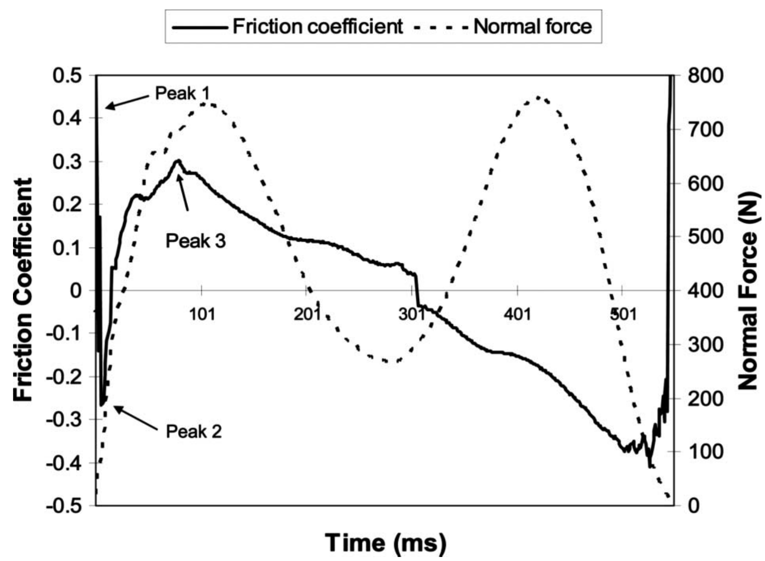

Figure 1: Example of normal force and instantaneous COF during stance.[26]

The RCOF has been correlated with several kinematic gait parameters linked to risk of slipping including: step time and step length, foot-floor angle and shank angle at heel contact, angular velocity of the foot, and linear velocity and acceleration of the heel at heel contact.[15, 24-30] Ankle, knee, and hip moments, walking speed, loading rate, and braking shear, have also been correlated with RCOF.[15, 24]

A slip occurs when extrinsic factors present a risk of slipping to which the intrinsic factors fail to adapt.[19] The relationship between available COF and RCOF is an effective way of evaluating the interaction between intrinsic and extrinsic factors, giving a reliable estimate of the risk of slipping. To assess the risk of slipping, most researchers only look at the RCOF because obtaining reliable measurements of the available COF between the shoe and floor is very challenging.[26]

Slip Induced Gait Alterations

Slips are commonly studied in laboratory settings in an effort to improve the understanding of the intrinsic factors contributing to slips and falls, and their interaction with extrinsic factors.[15] Resulting advancements in the understanding of slip mechanisms would aid in targeting effective slip and fall prevention strategies and improving risk assessment methods.[15, 21] One challenge with researching slips is maintaining natural gait in the laboratory to maintain internal and external validity of the results. Several studies have demonstrated that both awareness of a potential slip and prior slip experience alter gait.[15, 21, 24, 31]

Cham and Redfern (2002) investigated the effect of anticipating a slippery surface on gait. Although participants were instructed to walk naturally, a reduction in both RCOF and joint moments was observed when a slippery surface was anticipated. The observed reduction in RCOF was achieved through reductions in stance duration, loading rate, stride length, foot-ground angle, and angular foot velocity at heel contact. These gait alterations characterized a more cautious gait pattern, decreasing the risk of slipping.[15]

Similarly, Heiden et al. (2006) investigated the effects of slip risk awareness and prior slip experience on gait biomechanics. Both awareness and experience of a slip resulted in gait adaptations decreasing the risk of slipping, with larger changes observed when a participant had awareness and experience rather than awareness alone. The altered gait was characterized by decreases in the knee extension angle at heel contact, sheer force, braking impulse, propulsive impulse, and peak RCOF.[24] These gait alterations were measured during additional gait trials immediately after slipping, and no information on the time duration of these alterations has been reported.

Since many experimental slips occur with prior awareness[15, 19, 25, 32-34] or experience of a slip,[15, 19, 25, 33, 34] an altered gait would limit the internal and external validity of the results. To avoid experience-induced changes in gait, many researchers take a conservative approach and only slip participants one time.[15, 32, 35, 36] This approach, while effective, demands more time, resources, and participants than if participants could be slipped multiple times. It would be a great benefit to slip researchers to determine the time duration of gait alterations following the experience of a slip. After this duration, gait would have returned to its natural baseline and participants could theoretically be slipped again while maintaining the validity of the results.

Summary and Purpose

Falls are a significant source of injuries and fatalities in the United States, with a large portion resulting from slips. A better understanding of the intrinsic factors associated with the risk of slipping, and their interaction with extrinsic factors is sought in an effort to advance fall prevention strategies and risk assessment. Previous slipping studies have observed an alteration in gait in response to awareness of a slippery environment and prior slip experience, limiting the validity of results and the ability to generalize results. There is a need to better understand these protective gait adaptations to ensure the relevance of experimental findings to real world slips. This study aims to determine the time duration of gait alterations after a laboratory slip experience. Results from this study will aid in the experimental design of future studies involving laboratory slips.

REFERENCES

1. **Nawar EW, Niska RW, Xu J.** National hospital ambulatory medical care survey: 2005 emergency department summary. Emergency. 2007;110:4,000.
2. **Gillespie LD, Robertson MC, Gillespie WJ, et al.** Interventions for preventing falls in older people living in the community. Cochrane Database Syst Rev. 2009.
3. **Courtney TK, Sorock GS, Manning DP, et al.** Occupational slip, trip, and fall-related injuries - can the contribution of slipperiness be isolated? Ergonomics. 2001;44(13):1118-1137.
4. Slips, Trips, and Falls. National Safety Council, 2011.
5. **Alexander BH, Rivara FP, Wolf ME**. The cost and frequency of hospitalization for fall-related injuries in older adults. American journal of public health. 1992;82(7):1020-1023.
6. **Fuller G.** Falls in the elderly. Am Fam Physician. 2000;61(7):2159-2168.
7. **Kisner SM, Fosbroke DE**. Injury Hazards in the Construction Industry. Journal of Occupational and Environmental Medicine. 1994;36(2):137-143.
8. **Janicak CA.** Fall-Related Deaths in the Construction Industry. Journal of Safety Research. 1998;29(1):35-42.
9. **Cattledge GH, Hendricks S, Stanevich R.** Fatal occupational falls in the US construction industry, 1980–1989. Accident Analysis & Prevention. 1996;28(5):647-654.
10. **Shishlov KS, Schoenfisch AL, Myers DJ, et al.** Non-fatal construction industry fall-related injuries treated in US emergency departments, 1998–2005. American journal of industrial medicine. 2011;54(2):128-135.

11. Fatal Occupational Injuries by Major Event, 2011. U.S Bureau of Labor Statistics, USDoL, 2013.

12. **Rubenstein LZ.** Falls in older people: epidemiology, risk factors and strategies for prevention. Age and ageing. 2006;35(suppl 2):ii37-ii41.

13. **Sattin RW.** Falls among older persons: a public health perspective. Annual review of public health. 1992;13(1):489-508.

14. **Roudsari BS, Ebel BE, Corso PS, et al.** The acute medical care costs of fall-related injuries among the U.S. older adults. Injury. 2005;36(11):1316-1322.

15. **Cham R, Redfern MS.** Changes in gait when anticipating slippery floors. Gait & Posture. 2002;15(2):159-171.

16. **Leclercq S.** The prevention of slipping accidents: a review and discussion of work related to the methodology of measuring slip resistance. Safety Science. 1999;31(2):95-125.

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

18. **Gronqvist R.** Slips and falls. Biomechanics in ergonomics. 1999:351-375.

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

20. **Tisserand M.** Progress in the prevention of falls caused by slipping. Ergonomics. 1985;28(7):1027-1042.

21. **Grönqvist R, Abeysekera J, Gard G, et al.** Human-centred approaches in slipperiness measurement. Ergonomics. 2001;44(13):1167-1199.

22. **Grönqvist R, Chang WR, Courtney TK, et al.** Measurement of slipperiness: fundamental concepts and definitions. Ergonomics. 2001;44(13):1102-1117.

23. **Kim BJ, Robinson CJ.** Postural control and detection of slip/fall initiation in the elderly population. Ergonomics. 2005;48(9):1065-1085.

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

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

26. **Chang WR, Chang CC, Matz S.** Comparison of different methods to extract the required coefficient of friction for level walking. Ergonomics. 2012;55(3):308-315.

27. **Lockhart TE, Spaulding JM, Park SH.** Age-related slip avoidance strategy while walking over a known slippery floor surface. Gait & Posture. 2007;26(1):142-149.

28. **Kim S, Lockhart T, Yoon HY.** Relationship between age-related gait adaptations and required coefficient of friction. Safety Science. 2005;43(7):425-436.

29. **Burnfield JM, Powers CM.** The Role of Center of Mass Kinematics in Predicting Peak Utilized Coefficient of Friction During Walking*. Journal of forensic sciences. 2007;52(6):1328-1333.

30. **Redfern MS, Bidanda B.** Slip resistance of the shoe-floor interface under biomechanically-relevant conditions. Ergonomics. 1994;37(3):511-524.

31. **Siegmund GP, Heiden TL, Sanderson DJ, et al.** The effect of subject awareness and prior slip experience on tribometer-based predictions of slip probability. Gait & Posture. 2006;24(1):110-119.

32. **Brady RA, J. Pavol M, Owings TM, et al.** Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. Journal of Biomechanics. 2000;33(7):803-808.

33. **Marigold DS, Bethune AJ, Patla AE.** Role of the Unperturbed Limb and Arms in the Reactive Recovery Response to an Unexpected Slip During Locomotion. Journal of Neurophysiology. 2003;89(4):1727-1737.

34. **Marigold DS, Patla AE.** Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. Journal of Neurophysiology. 2002;88(1):339-353.

35. **Moyer B, Chambers A, Redfern MS, et al. Gait** parameters as predictors of slip severity in younger and older adults. Ergonomics. 2006;49(4):329-343.

36. **Troy KL, Donovan SJ, Marone JR, et al.** Modifiable performance domain risk-factors associated with slip-related falls. Gait & Posture. 2008;28(3):461-465.

CHAPTER 3 – AN EXPLORATORY STUDY INVESTIGATING THE TIME DURATION OF SLIP-INDUCED CHANGES IN GAIT

Introduction

Falls are a significant source of unintentional injury and medical costs in the United States. In 2005, there were more than 8.7 million emergency department visits made to U.S. hospitals due to fall-related injuries, making up 20% of all injury visits.[1] Additionally, the National Safety Council reported that falls are the second-leading cause of unintentional death in homes and communities, resulting in more than 25,000 fatalities in 2009.[2] Claims for occupational fall-related injuries make up about 25% of all worker's compensation costs in the United States, estimated to total more than $6 billion annually.[3] The high rates of fall-related injuries and associated medical costs highlight the importance of research into the mechanisms and prevention of falls.[4]

Slipping events are responsible for the loss of balance that leads to a large proportion of falls.[3, 5-7] Courtney et al. (2001) reported that slips contributed to 40-50% of reported fall-related injuries.[3] A slip, as defined by Grönqvist (1999), is 'a sudden loss of grip, often in the presence of liquid or solid contaminants and resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity.'[8] The causes of slips are complex, involving the interaction of several factors, both intrinsic (human factors) and extrinsic (environmental factors).[7, 9-11]

The frictional properties of the interface between the shoe and floor are the primary environmental determinants of a slipping event.[9, 11] In particular, the available coefficient of friction between the shoe and floor is determined largely by shoe and floor materials and environmental conditions. The required coefficient of friction (RCOF) is the minimum COF necessary at the shoe-floor interface to prevent slipping.[12] The risk of slipping increases when the RCOF approaches or exceeds the available COF.[7, 9, 12] To assess the risk of slipping, most researchers only look at the RCOF because obtaining reliable measurements of the available COF between the shoe and floor is very challenging.[12] Increases in RCOF indicate an increased risk of slipping. The RCOF is determined by first calculating the ratio of the shear to normal ground reaction force during stance. The local maximum of this ratio at 10-20% of stance is typically used as the RCOF because it is at this point that slipping is thought to most likely lead to a fall.[12] The RCOF has been correlated with several kinematic gait parameters also related to risk of slipping.[5, 12-18]

The biomechanics of slips are commonly studied in laboratory settings in an effort to improve the understanding of slip mechanisms, slip and fall prevention strategies, and risk assessment methods.[5, 11] One challenge in studying slips is to maintain natural gait patterns in the lab. Previous studies have demonstrated that both awareness of a slippery environment and prior slip experience alter an individual's gait, which may limit the external validity of any experimental results obtained after these changes occur.[5, 11, 13] Therefore, most researchers only slip participants once in this type of experiment.[5, 11, 13, 19-21] Describing the acute changes in gait after an induced slip may allow participants to be slipped more than once, but after an appropriate delay to allow gait to return to a natural baseline. This could substantially improve the efficiency of such experiments, as fewer participants would be needed, thereby reducing the time and resources for participant recruitment, medical screenings, and experimentation. It would also allow the use of within-subject experimental designs (or at least repeated measures for a subset of factors), which have improved statistical power over between-subject designs.[22]

Therefore, the goal of this study was to determine the time duration of slip-induced changes in RCOF during laboratory testing. Changes in other related gait parameters were also investigated. Results from this study will aid in the experimental design of future studies involving laboratory slips. An understanding of the effective time period of gait adaptations could allow researchers to slip participants more than once, while ensuring results are descriptive of natural, unexpected slips.

Methods

Thirty-one young male adults (age: 21 ± 2.3 years, height: 179.1 ± 7.8 cm, mass: 79.8 ± 11.8 kg) were recruited from the university population to participate in the study. All participants were free from self-reported musculoskeletal and neurological disorders affecting gait or balance. The Virginia Tech Institutional Review Board approved this study, and informed consent was obtained from participants prior to participation.

Participants completed four experimental sessions during which gait measures were collected for several walking trials (6-13 acceptable trials). Participants were made aware of a possible slip during any walking trial, and were instructed to walk naturally. During the first three sessions, baseline gait measures were collected. During the third session, after gait measurements, participants were exposed to an unexpected slip during a randomly selected trial. Walking trials were then repeated approximately 10 minutes after the slip. Participants returned for the fourth session either one, two, four, or six weeks after the slip. Gait measures from the four sessions were used to determine amplitude and duration of the changes in gait after an induced slip. During each session, participants wore standard shoes to prevent variation in the frictional properties of the shoe-floor interface, and a safety harness attached to a track above the walkway to prevent slip-related falls.

At the start of the first session, a self-selected gait speed between 1.5 and 2 m/s was determined for each participant by asking them to walk at a purposeful speed (slightly faster than comfortable) along a 9m linoleum walkway in the laboratory. Participants were asked to maintain this speed during all subsequent walking trials, and trials with a gait speed not within a fixed range (-0.0525 m/s to +0.0975 m/s from mean speed) were repeated with verbal feedback from the investigators to increase or decrease speed. Walking speed was experimentally controlled to avoid changes in speed from confounding our measurements of RCOF. Participants were given three practice trials at the beginning of each session to adjust to the environment and re-establish their gait speed from the first session (if necessary). After the self-selected gait speed was determined, data from approximately 10 acceptable walking trials (appropriate speed and foot placement with respect to a force platform) were collected. During these and all other walking trials, participants were attempting to retain a memorized set of letters, numbers, or symbols to divert their attention from walking and a potential slip. Once reaching the end of the walkway, participants were instructed to sit on a stool with their back to the walkway and memorize a new set of information until notified by the investigator to turn around and prepare for the next trial. Session two and the beginning of session three each involved collecting data during approximately10 more acceptable walking trials at the appropriate speed.

After the initial gait trials during session three, a thin layer of vegetable oil was applied with a paint roller to a middle portion of the walkway while the participants had their back to the walkway and were distracted with their memorization task. To prevent auditory or visual cues of the contaminant, participants wore noise protection earmuffs, nature sounds were played, and the lighting was dimmed throughout all sessions. Slips of the stance foot of at least 3 cm during early stance were characterized as a successful slip trial. If participants were unsuccessfully slipped, the walkway and shoes were cleaned and dried, and another slip was attempted after a few additional walking trials. After a successful slip trial, the walkway and shoes were cleaned and dried, restoring their original state, and walking trials were immediately continued to document post-slip gait alterations. The fourth session was one, two, four, or six weeks after the slip, and involved approximately10 additional walking trials. This study was performed in waves. Therefore, participants were placed in a follow-up group based on the time of their participation rather than random assignment. Participants were compensated $40 for completing the four hour-long sessions, and an additional $10 was awarded based on memorization activity performance.

During each trial, the three-dimensional position of selected anatomical landmarks were sampled at 100 Hz using a six-camera Vicon motion analysis system (Vicon Motion Systems Inc., Centennial, CO), and ground reaction forces were sampled at 1000 Hz using a force platform (Bertec Corporation, Columbus, OH). Marker locations included the inferior tip of the right scapula, the heel and tip of each shoe, and the right and left lateral malleolus (ankle) and lateral femoral epicondyle (knee).

Marker position and force plate data were low-pass filtered at 5 and 7 Hz, respectively (eighth-order zero-phase-shift Butterworth filter) and used to calculate eight dependent variables using MATLAB R2012a (The Mathworks Inc., Natick, MA) to quantify gait: RCOF, peak braking shear, loading rate, foot angle at heel contact, shank angle at heel contact, stance time, step time, and step length. The RCOF was the primary dependent variable, as it is the most closely related to risk of slipping. The additional variables were included to analyze the mechanisms by which RCOF was altered. The RCOF was calculated as a local maximum in the ratio between shear and normal ground reaction forces observed during early stance (10-20% of stance), as described by Chang et al. (2012).[12] Peak braking shear was the maximum ground reaction force in the posterior direction and was normalized to body mass, and loading rate was the average rate of vertical ground reaction force increase from impact with the force platform to the first peak in the vertical component of the ground reaction force and was normalized to body mass. Foot angle was the angle between the bottom of the foot and the floor in the sagittal plane (foot flat on floor was 0 degrees), and shank angle was the angular deviation of the shank from the anatomical position in the sagittal plane. Stance time, step time, and step length were defined as the duration of time from heel contact to toe-off, and the time and distance between heel contact and contralateral-limb heel contact respectively.

A repeated-measures ANOVA and subsequent contrasts were used to investigate the changes in each parameter from baseline at the post-slip and follow-up sessions. First, slip-induced changes in the dependent variables were investigated by categorizing the data of each of the 31 participants into four groups (baseline 1, baseline 2, baseline 3, post-slip). A repeated-measures ANOVA was performed followed by a contrast between the three baseline sessions and the post-slip session (baseline1, baseline2, baseline3 vs. post-slip). Next, to investigate whether the altered post-slip dependent variables returned to baseline after each break length, a separate statistical analysis was performed for the group of participants assigned to each break length. The data were categorized into five groups (baseline 1, baseline 2, baseline 3, post-slip, follow-up). A repeated-measures ANOVA was performed followed by 2 contrasts: a contrast between the baseline sessions and the post-slip session (baseline 1, baseline 2, baseline 3 vs. post-slip) to determine whether the post-slip changes were detectable in the smaller group of participants and a contrast between the baseline sessions and the post-break session (baseline 1, baseline 2, baseline 3 vs. follow-up) to determine if the dependent variables remained significantly different from baseline during follow-up testing. Statistical analyses were performed using JMP 9 (SAS Institute Inc., Cary, NC) with a significance level of $p = 0.05$.

Results

To illustrate typical trial-to-trial variability in RCOF for each participant, representative RCOF data from two participants are shown in Figure 2. The typical range of RCOF was 0.03-0.04 for each participant during each testing session. These data also illustrate two common trends in RCOF over the five testing sessions. The first trend (Figure 2, left) showed a relatively constant median RCOF throughout the three baseline sessions, a decrease in RCOF immediately after slipping, and an increase back to near baseline after six weeks. The second trend (Figure 2, right) showed the same relatively constant median RCOF at baseline, a decrease in RCOF immediately after slipping, but no recovery back toward baseline after six weeks.

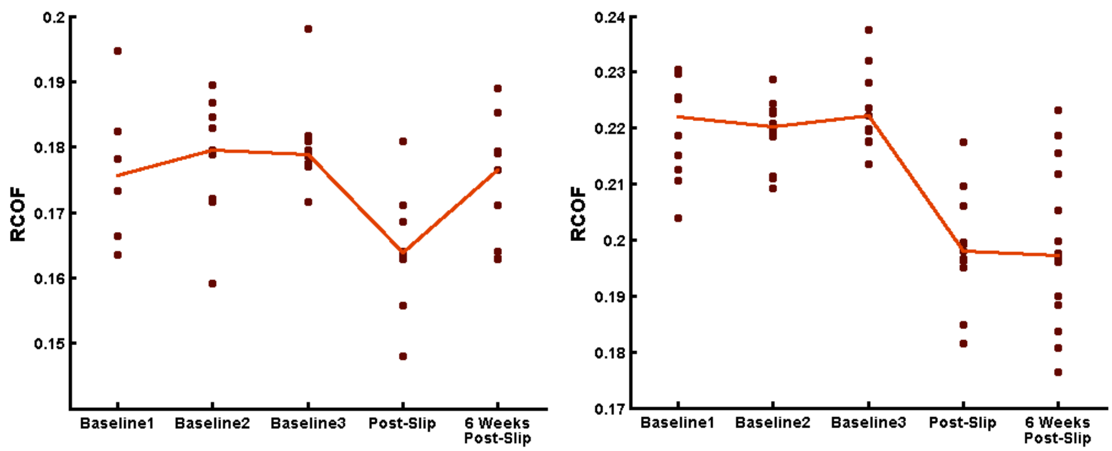

Figure 2: RCOF data from two representative participants. Each individual walking trial is represented by a filled circle, and a trend line connects the median at each session. These plots illustrate the intra-subject variability, and two typical trends in RCOF.

To better illustrate the varying trends in RCOF between participants over the five testing sessions, RCOF data from all participants are shown in Figure 3. The median RCOF value across all baseline sessions and across all participants was 0.20, and the range of these values was 0.09. Thirty of 31 participants demonstrated a decrease in RCOF immediately after slipping, and the percentage of participants who showed an increase in RCOF toward baseline increased as the break period lengthened (Table 1). One week after slipping, 44% (4 out of 9) of participants showed an increase in RCOF toward their baseline value. Two weeks after slipping, 50% (2 out of 4) of participants showed an increase in RCOF toward their baseline value. Four weeks after slipping, 57% (4 out of 7) of participants showed an increase in RCOF toward their baseline value. Six weeks after slipping, 73% (8 out of 11) of participants showed an increase in RCOF toward their baseline value.

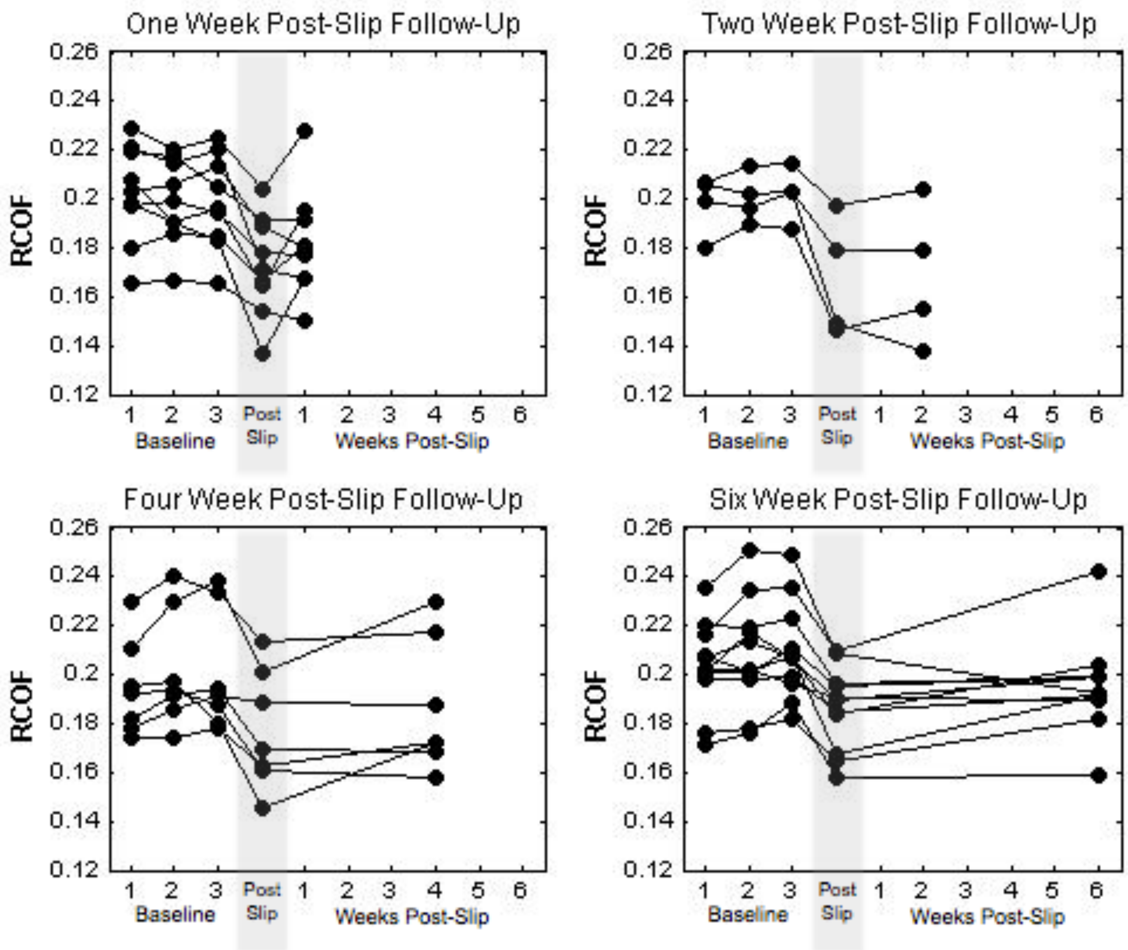

Figure 3: Mean RCOF trend for each individual participant, showing the qualitative variability in mean RCOF between participants.

The median trend in RCOF across all participants is shown in Figure 4. This trend shows no significant changes in RCOF across the three baseline sessions (p = 0.099*)*, a 12% (mean = 0.03) decrease in RCOF immediately after slipping ($p < 0.001$), and a gradual increase toward baseline over weeks 2-6 after the slipping (but these values remained statistically different from the baseline value; $p < 0.01$).

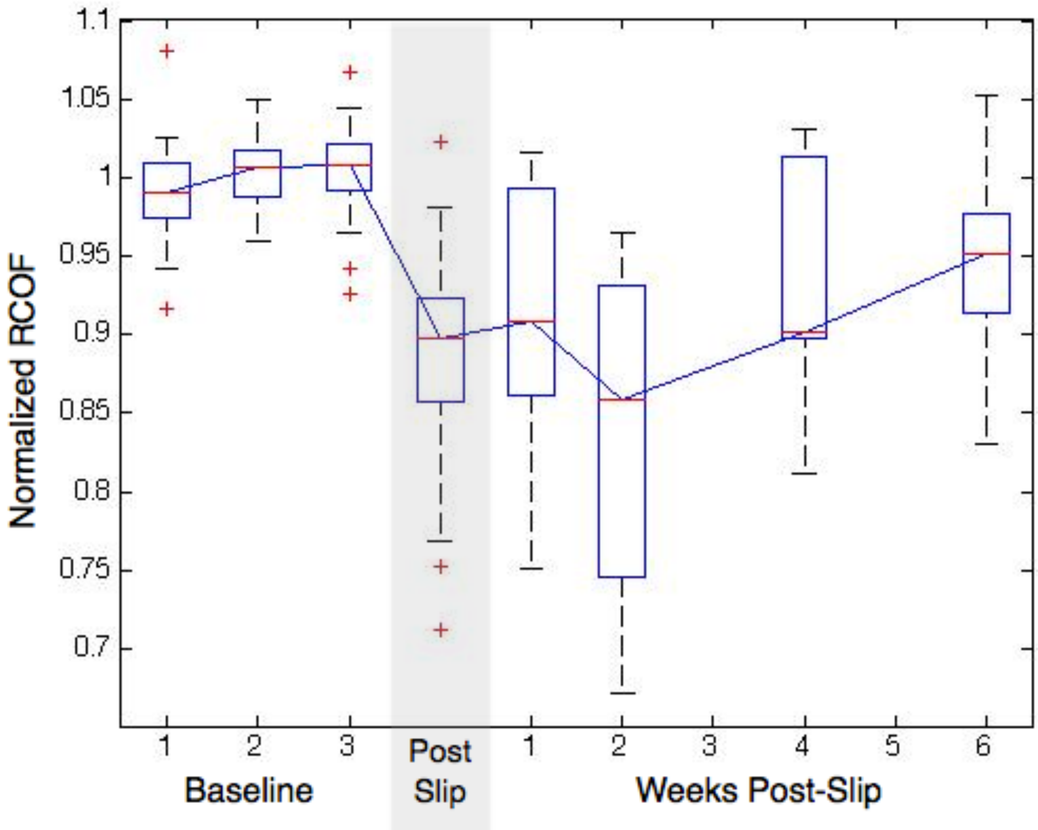

Figure 4: Median RCOF at each session for all subjects normalized to baseline. The box and whisker plot at each session shows the median at the central mark, and the edges of the box represent the 25th and 75th percentiles. The whiskers extend to the most extreme points that are not outliers, which are plotted individually. Outliers are points larger than $q_3 + 1.5(q_3 - q_1)$ or smaller than $q_1 - 1.5(q_3 - q_1)$, where q_1 and q_3 are the 25th and 75th percentiles respectively.

Other dependent variables showed varied responses to slipping and follow-up (Figure 5). After slipping, peak braking shear decreased an average of 11% (0.26 N/kg), loading rate decreased an average of 3% (2.43 N/s/kg), and foot angle decreased an average of 4% (1.17 degrees). All three of these dependent variables remained statistically different from baseline one, two, four, and six weeks later during follow-up testing. However, the percentage of participants who showed an increase in peak braking shear and loading rate toward baseline values at follow-up was larger as the time duration increased (Table 1), similar to the trend observed in RCOF. Shank angle, stance time, step time and step length, all lacked any consistent trend and showed no change after slipping or after follow-up.

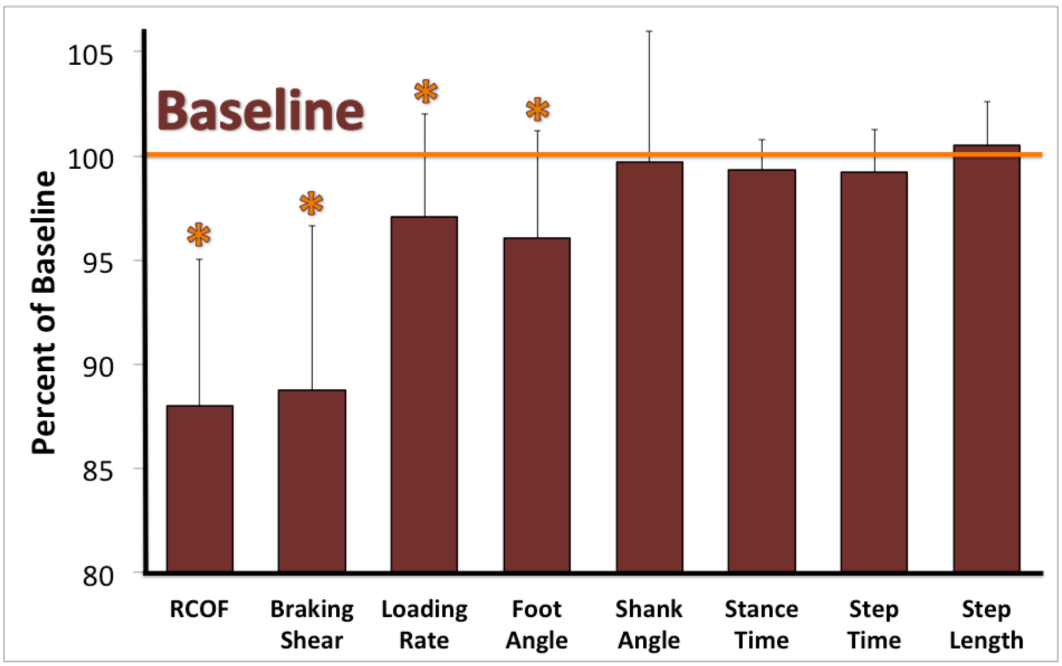

Figure 5: Mean gait parameters of all 31 participants after slipping as a percentage of the baseline value. Across all participants, the RCOF, braking shear, loading rate, and foot angle after a slipping decreased significantly from the baseline values, denoted by an asterisk (*). Shank angle, stance time, step time, and step length did not deviate from baseline on average.

Table 1: The percentage of participants with a post-slip change in significant dependent variables and the percentage of participants that showed an increase toward baseline one, two, four, and 6 weeks later out of all participants with a post-slip change.

Dependent Variables Affected by Slipping	Percentage of Participants Demonstrating a Post-Slip Decrease	Percentage of Participants that Increased Towards Baseline at Each Post-Slip Time Period of Those Who Decreased Post-Slip			
		1 Week	2 Weeks	4 Weeks	6 Weeks
RCOF	97%	44% (4 of 9)	50% (2 of 4)	57% (4 of 7)	73% (8 of 11)
Peak Braking Shear	94%	29% (2 of 7)	50% (2 of 4)	57% (4 of 7)	64% (7 of 11)
Loading Rate	55%	60% (3 of 5)	67% (2 of 3)	14% (1 of 7)	75% (3 of 4)
Foot Angle	65%	83% (5 of 6)	33% (1 of 3)	25% (1 of 4)	71% (5 of 7)

Discussion

The goal of this study was to determine the time duration of slip-induced changes in RCOF during laboratory testing. RCOF during level gait was measured on three separate days before slip, immediately after slipping, and either one, two, four, or six weeks later for each participant. RCOF exhibited no changes among baseline measurements, an average 12% decrease immediately after slipping, and a gradual increase toward baseline 4-6 weeks after slipping. However, the RCOF remained statistically lower than baseline for all follow-up sessions up to six weeks after slipping. As such, these results indicate that the duration of slip-induced changes in RCOF during laboratory testing persist for at least six weeks.

The 12% decrease in RCOF and changes in other gait parameters immediately after slipping were consistent with other studies and suggest a more cautious gait to reduce the risk of slipping. Cham and Redfern (2002) reported a 5-12% decrease in RCOF from baseline (mean baseline RCOF = 0.18) after a slip experience when participants were assured they would not be slipped again,[5] and Lockhart et al. (2003) reported a 20% decrease in RCOF from a baseline (mean baseline RCOF = 0.20).[14]

Changes in other gait parameters similar to those found here were reported by Cham and Redfern (2002), Lockhart et al. (2003), Heiden et al. (2006), and Marigold and Patla (2002).[5, 13, 17, 23] These parameter changes include a 0.42 N/kg[13] and 0.5 N/kg[5] decrease in peak braking shear (current study: 0.26 N/kg decrease), a 5.9 N/s/kg[13] and 9.5 N/s/kg[23] decrease in loading rate (current study: 2.43 N/s/kg decrease), a 3.7,[5] 4.5,[23] and 6.8[13] degree decrease in foot angle (current study: 1.17 degree decrease), a 0.3 degree[5] decrease in shank angle, and a 5 degree/s[5] decrease in foot angular velocity at heel contact.[5, 13, 14, 23] The changes in gait after slipping observed in the present study were consistent with the trends observed in other studies, but the magnitude of the changes was smaller. The reason for this discrepancy may be due to the fact that our participants were aware of a possible slip during all trials whereas the other studies collected baseline values while participants were assured they would not slip. We did this intentionally because we wanted the participants' level of awareness of a possible slip to be constant across all experimental sessions, only varying the experience of slipping.

The lack of change in the spatial and temporal gait parameters after the slip experience was unexpected. Perhaps related to this lack of a change, previous studies showed inconsistent results with respect to changes in step length[5, 14] and stance duration[5, 13] following a slip. Quicker, shorter steps are indicative of a protective gait with a reduced risk of slipping, yet no trends (statistically significant or otherwise) were consistently observed in stance time, step time, or step length after the slip experience or any number of weeks thereafter. The control of walking speed in this study may have mitigated the expected variation of these parameters.

The decrease in RCOF observed after slipping was 0.03 on average. A change in RCOF of this magnitude can have a significant effect on the probability of slipping, depending on how close RCOF and COF are in magnitude. Burnfield and Powers (2006) demonstrated that it is possible to predict a slip event based on the difference between the coefficient of available friction and the required coefficient of friction (COF – RCOF).[24] They reported a 5% probability of a slip occurring when the RCOF was 0.047 lower than the COF and a 50% probability of s slip occurring when the RCOF was 0.006 greater than COF.[24] In an environment with a constant COF, a decrease in RCOF of 0.053 increases the probability of slipping by 45%. Therefore, the average decrease in RCOF of 0.03 observed in this study is a significant magnitude, greatly reducing the risk of slipping when RCOF and COF are similar in magnitude.

Although the RCOF remained statistically lower than baseline during all follow up sessions, the average RCOF showed a trend towards baseline over weeks 2-6. The percent of participants who showed an increase in RCOF toward baseline was 44% at one week, 50% at two weeks, 57% at four weeks, and 73% at six weeks, indicating that the RCOF was gradually returning to baseline more consistently as the time duration increased. A similar trend was observed in peak braking shear and loading rate over the six weeks after slipping. This indicates that RCOF and associated gait parameters may fully recover to baseline over a longer period of time after a slip experience. A continuation of this study is currently ongoing to determine if RCOF remains statistically different from baseline three months after slipping.

The experimental design employed in this study involved each participant performing a single follow up session one or more weeks after slipping. This design was chosen because it minimized the number of experimental sessions during which participants could not be slipped. An alternative experimental design would be to have participants complete multiple follow-up sessions at shorter intervals until gait returned to baseline. However, it was felt that this design would be inefficient and impractical for future slipping studies in that it would likely require many experimental sessions without data being collected. Moreover, if we had used this alternative design, it would be unclear if gait returned to baseline because of the time duration since slipping, or because of the multiple follow-up sessions completed.

This study found that post-slip gait adaptations indicative of cautious walking have long-lasting effects, enduring up to six weeks. While this finding is a limitation for studies desiring to slip participants multiple times, it may support training interventions for improved slip prevention and balance recovery. Researchers have proposed that slipping or tripping individuals periodically in a controlled environment as a training intervention could alter gait to reduce the risk of slips and trips, or improve balance recovery ability.[25-27] This study indicated that the changes in behavior induced by a single slip last up to six weeks, which suggests that a slip or trip training intervention may also have lasting benefits.

Several limitations warrant discussion. First, it is unclear if the slip induced gait changes observed in the laboratory endure outside of the laboratory. The informed consent process used in this study made participants aware of a potential slip, which may have a heightened their awareness of slipping more than is typical in a natural environment. As such, it is possible that the changes in gait were limited to the laboratory. Additionally, this study only investigated the changes in gait after slipping.

Therefore, no conclusions can be made about changes in slip recovery strategies following a slip. Finally, this study was limited to young adult males to avoid potential age and gender effects. It is unclear if the time duration of slip-induced changes in gait observed in this study is similar among older adults.

In conclusion, slip-induced changes in RCOF persisted for up to six weeks when walking in a laboratory. Additional ongoing work will assess if changes persist for three months and will supplement the results reported here. A more complete understanding of the effective time period of post-slip gait alterations will aid in the experimental design of future studies involving laboratory slips, potentially introducing the ability to slip participants multiple times while preserving external validity of the results, and could have beneficial implications for trip or slip training interventions.

REFERENCES

1. **Nawar EW, Niska RW, Xu J.** National hospital ambulatory medical care survey: 2005 emergency department summary. Emergency. 2007;110:4,000.
2. Slips, Trips, and Falls. In Council NS, (Ed) 2011.
3. **Courtney TK, Sorock GS, Manning DP, et al.** Occupational slip, trip, and fall-related injuries can the contribution of slipperiness be isolated? Ergonomics. 2001;44(13):1118-1137.
4. **Roudsari BS, Ebel BE, Corso PS, et al.** The acute medical care costs of fall-related injuries among the U.S. older adults. Injury. 2005;36(11):1316-1322.
5. **Cham R, Redfern MS.** Changes in gait when anticipating slippery floors. Gait & Posture. 2002;15(2):159-171.
6. **Leclercq S.** The prevention of slipping accidents: a review and discussion of work related to the methodology of measuring slip resistance. Safety Science. 1999;31(2):95-125.
7. **Redfern MS, Cham R, Gielo-Perczak K, et al.** Biomechanics of slips. Ergonomics. 2001;44(13):1138-1166.
8. **Gronqvist R.** Slips and falls. Biomechanics in ergonomics. 1999:351-375.
9. **Hanson JP, Redfern MS, Mazumdar M.** Predicting slips and falls considering required and available friction. Ergonomics. 1999;42(12):1619-1633.
10. **Tisserand M.** Progress in the prevention of falls caused by slipping. Ergonomics. 1985;28(7):1027-1042.

11. **Grönqvist R, Abeysekera J, Gard G, et al.** Human-centred approaches in slipperiness measurement. Ergonomics. 2001;44(13):1167-1199.

12. **Chang WR, Chang CC, Matz S.** Comparison of different methods to extract the required coefficient of friction for level walking. Ergonomics. 2012;55(3):308-315.

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

14. **Lockhart TE, Spaulding JM, Park SH.** Age-related slip avoidance strategy while walking over a known slippery floor surface. Gait & Posture. 2007;26(1):142-149.

15. **Kim S, Lockhart T, Yoon HY.** Relationship between age-related gait adaptations and required coefficient of friction. Safety Science. 2005;43(7):425-436.

16. **Burnfield JM, Powers CM.** The Role of Center of Mass Kinematics in Predicting Peak Utilized Coefficient of Friction During Walking. Journal of forensic sciences. 2007;52(6):1328-1333.

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

18. **Redfern MS, Bidanda B.** Slip resistance of the shoe-floor interface under biomechanically-relevant conditions. Ergonomics. 1994;37(3):511-524.

19. **Brady RA, J. Pavol M, Owings TM, et al.** Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. Journal of Biomechanics. 2000;33(7):803-808.

20. **Moyer B, Chambers A, Redfern MS, et al.** Gait parameters as predictors of slip severity in younger and older adults. Ergonomics. 2006;49(4):329-343.

21. **Troy KL, Donovan SJ, Marone JR, et al.** Modifiable performance domain risk-factors associated with slip-related falls. Gait & Posture. 2008;28(3):461-465.

22. **Portney LG, & Watkins, MP.** Foundations of Clinical Research - Applications to Practice. Upper Saddle River, NJ: Prentice Hall Health 2000.

23. **Marigold DS, Patla AE**. Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. Journal of Neurophysiology. 2002;88(1):339-353.

24. **Burnfield, J.M. and C.M. Powers**, *Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance.* Ergonomics, 2006. **49**(10): p. 982-995.

25. **Owings TM, Pavol MJ, Grabiner MD.** Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. Clinical Biomechanics. 2001;16(9):813-819.

26. **Bieryla KA, Madigan ML, Nussbaum MA.** Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. Gait & Posture. 2007;26(2):208-213.

27. **Pavol MJ, Runtz EF, Edwards BJ, et al.** Age influences the outcome of a slipping perturbation during initial but not repeated exposures. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences. 2002;57(8):M496-M503.

APPENDIX A – Annotated List of Figures

Figure 1: Example of normal force and instantaneous COF during stance.

Chang WR, Chang CC, Matz S. Comparison of different methods to extract the required coefficient of friction for level walking. Ergonomics. 2012;55(3):308-315.

Fair Use determination attached.

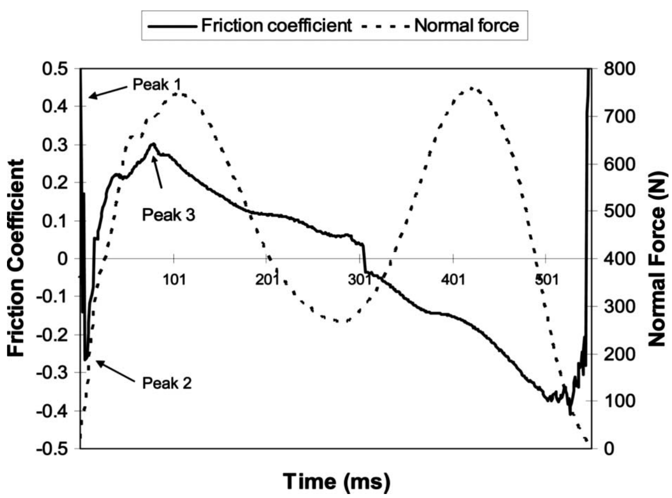

Figure 2: RCOF data from two representative participants. Each individual walking trial is represented by a filled circle, and a trend line connects the median at each session. These plots illustrate the intra-subject variability, and two typical trends in RCOF.

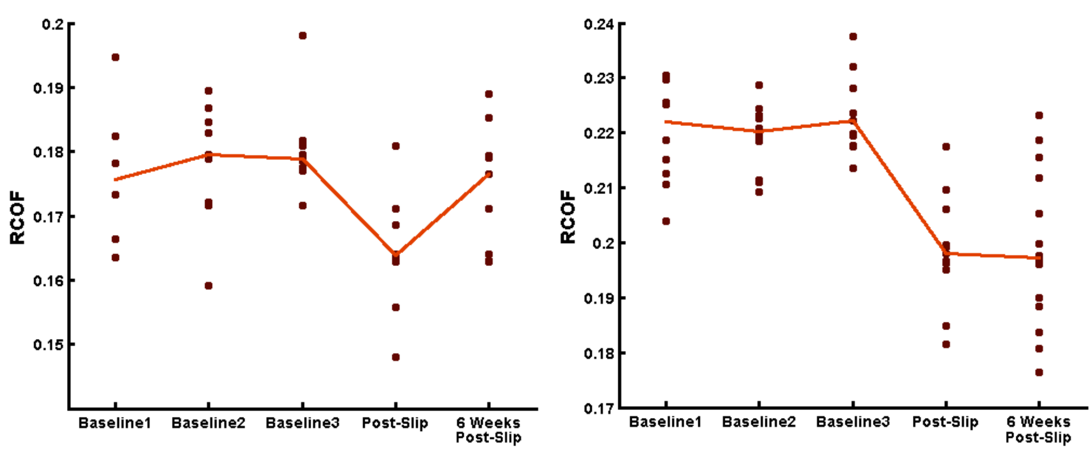

Figure 3: Mean RCOF trend for each individual participant, showing the qualitative variability in mean RCOF between participants.

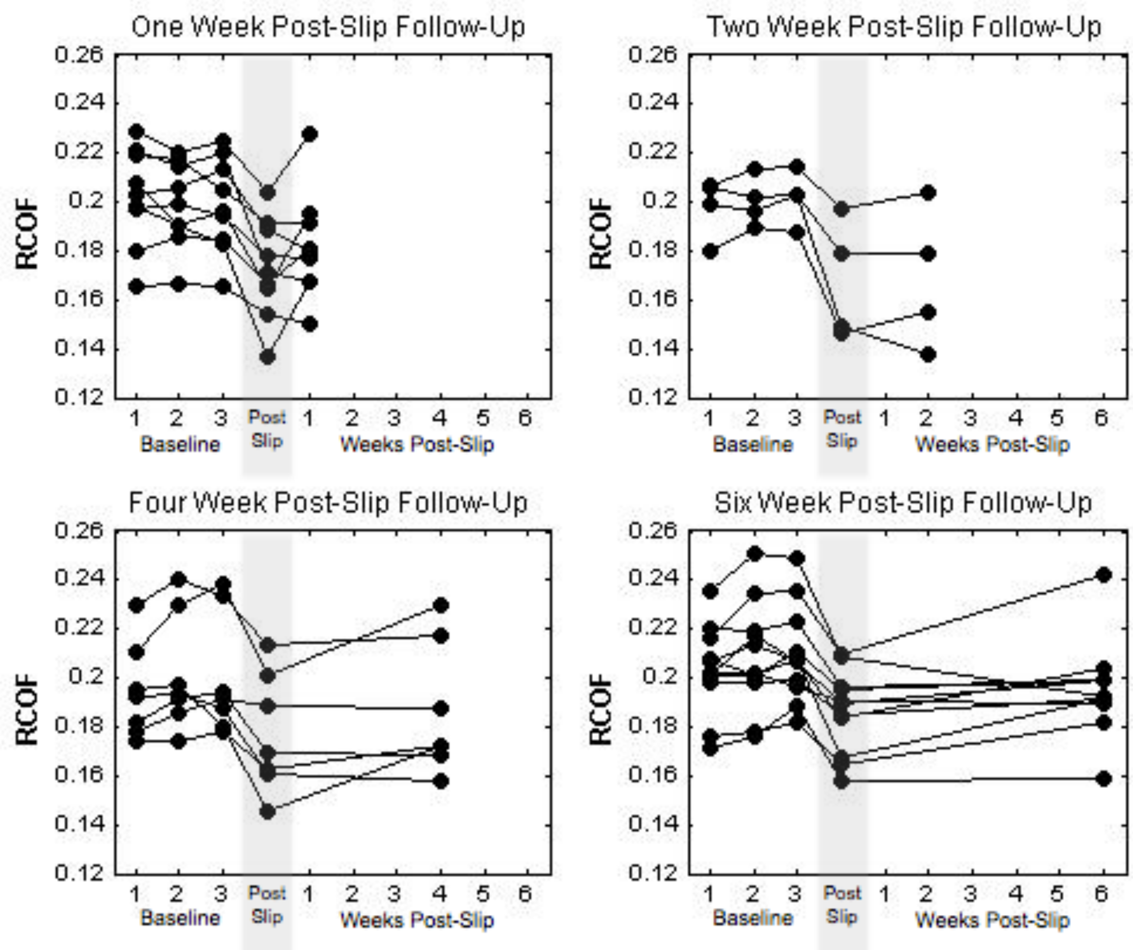

Figure 4: Median RCOF at each session for all subjects normalized to baseline. The box and whisker plot at each session shows the median at the central mark, and the edges of the box represent the 25th and 75th percentiles. The whiskers extend to the most extreme points that are not outliers, which are plotted individually. Outliers are points larger than $q_3 + 1.5(q_3 - q_1)$ or smaller than $q_1 - 1.5(q_3 - q_1)$, where q_1 and q_3 are the 25th and 75th percentiles respectively.

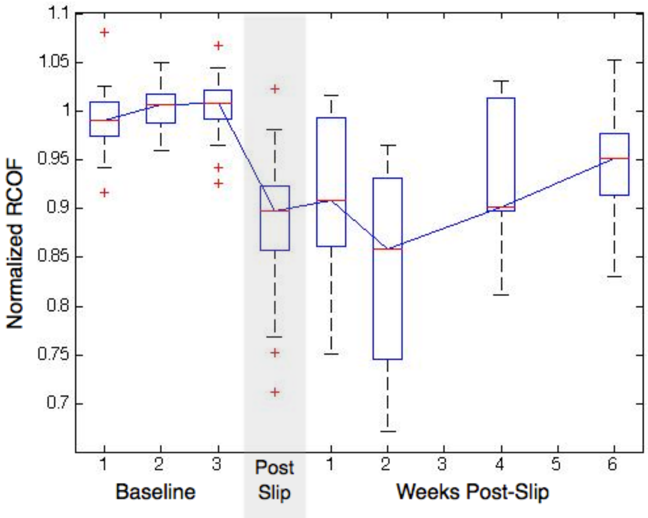

Figure 5: Mean gait parameters of all 31 participants after slipping as a percentage of the baseline value. Across all participants, the RCOF, braking shear, loading rate, and foot angle after a slipping decreased significantly from the baseline values, denoted by an asterisk (*). Shank angle, stance time, step time, and step length did not deviate from baseline on average.