CENTER OF MASS DYNAMICS AND SLIP SEVERITY

by

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The National Safety Council listed falls as the third ranked cause (14.6%) of unintentional deaths in the general population of the US. It is postulated that an attempt to control the COM is employed to prevent falls during perturbed gait. The goal of this research was to gain an understanding of (1) the relationship between COM dynamics at slip initiation and slip severity, and (2) how individuals control their COM dynamics when warned about the possibility of slipping (anticipatory control). The dynamics of the body's COM during slips may reveal insights into the biomechanical reasons behind the high prevalence of slip-precipitated falls in the elderly. The findings may also be helpful in differentiating between postural strategies that successfully recover balance and responses that result in falls.

Sixteen healthy young (20-35 yrs) and 11 older (55-70 yrs) subjects were exposed to an unexpected slip (no prior knowledge of the floor's contaminant condition), and alert slip (warned of the potential contamination), and known slip after two baseline walking trials. Body motion from 79 VICON markers attached to the body was sampled at 120 Hz. Segmental mass was generated using a segmental analysis. For an unexpected slip, maintaining the COM closer to the leading leg, an elevated COM position and fast medial-lateral COM transfers to the slipping leg at heel contact were associated with an increase in slip severity. For anticipation conditions (alert and known), COM placement and velocity was geared toward continuing the gait cycle. Age was significant in regards to COM position variables.

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PREFACE

I would like to thank my committee members, Dr. Richard Debski, Dr. Jean McCrory, and Dr. Mark Redfern, for taking the time to serve on my committee and offering words of encouragement, insight, and advice. I also would like to thank all the members of the Human Movement and Balance Lab for their continuous support. I also wish to thank Lynette Spataro and Joan Williamson for always being there to guide me along the way. Finally, I am tremendously grateful to my thesis advisor, Dr. Rakié Cham. Her dedication, patience and support helped me complete my thesis research. Dr. Cham's guidance throughout the years made her both a mentor and friend. Most importantly, I would like to thank my family for their love and support. I would never have gotten as far in life without their encouragement.

1.0 INTRODUCTION

1.1 SCOPE OF THE PROBLEM

Slips, trips, and falls (STF) and their associated injuries and deaths are a serious concern both in and outside the workplace. Overall, the National Safety Council reported 14,500 deaths due to falls in 2002 and listed falls as the third ranked cause (14.6%) of unintentional injury deaths in the general population in the United States [1]. In the workplace, the incidence of nonfatal falls was nearly 19% in 2001 in the United States [2], while the prevalence of fatal falls ranked third below traffic accident fatalities and poisonings (Figure 1). Falls are often initiated by slip events. For same level occupational falls, slipping is the most common triggering event (43-50% of the cases), followed by tripping (18%) and loss of balance (14%) [2, 3, 4].

Fall related injuries are severe and impart a heavy economic burden on society. Workers suffer a multitude of injuries resulting from STFs; including sprains and strains, contusions and crushings, fractures, superficial injuries, and lacerations [5]. Over 21% of reported occupational disabling injuries in the United States are caused by STFs, the most common injuries being lower limb and wrist fractures [4]. The economic relation between slip-precipitated falls and cost can be observed in insurance claims by the workforce in the United States. Slip and fall injuries comprised over 24% of the total cost of occupational insurance claims in the U.S. and included over 16% of the total number of occupational insurance claims seen in 1989 and 1990. Over 65% of these claims were due to falls on the same level, incurring an average cost of $4363 per claim [6]. The economic detriment of falls and severity of injuries is also reflected in the number of days away from work (Figure 2). The increased incidence of sick leave economically impacts the cost of doing business through lost time as well as increasing worker compensation payments. Similar findings were reported in Great Britain: STFs are the second most leading cause for occupational injuries and cost over $247 million in medical costs and lost output each year [5]. These falls-related occupational trends cause similar concerns in the general population. In 1985, falls in the general population affected over 11 million people in the United States resulting in a lifetime cost to the nation of $37 billion [7].

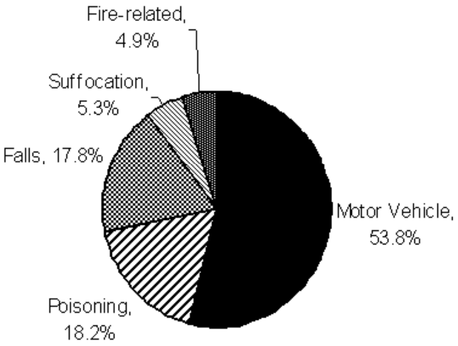

Figure 1: Unintentional Deaths by Cause [2].

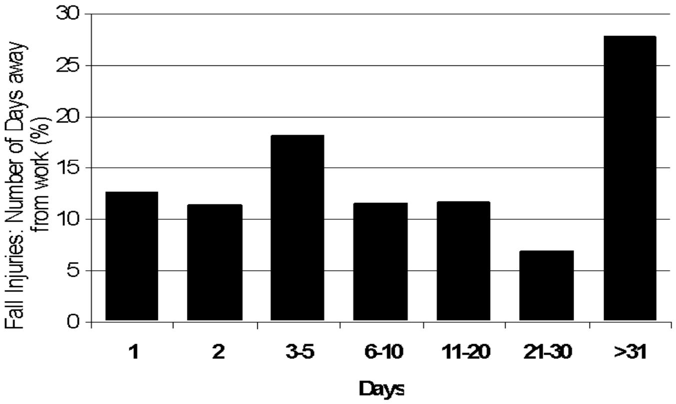

Figure 2: Number of days away from work due to falls [2].

The probability of falling as well as severity of fall-related injuries increases with age. Specifically, the risk for an STF accident is 1.5 times greater in workers aged 56 years and above compared to the findings in younger individuals between the ages of 21 and 25 years [5]. Occupational falls, one of the four leading causes of death for workers 65 and older, are responsible for 13% of deaths in that age group, which is 4 to 14 times the rate from workers aged 16 to 64 years [8]. Finally, over 50% of fatal falls in the United States workforce occur to adults 45 years and older (Figure 3). Similarly, outside the workplace, the average annual risk of falling for an older adult over 65 years ranges from 30 to over 50%, meaning roughly one in three older adults fall each year [9, 10]. Furthermore, older adults over 75 years of age have almost three times the incidence of falls compared to older adults aged 60-75 years in the general population in the United Kingdom [11]. In a study based in a hospital in New Zealand, nearly 90% of documented hip fractures in the elderly population involved a fall, with 75% of them taking place indoors and the remainder outdoors [12]. Falls-related injuries incurred an average cost of $4000 to an individual over 65 years of age in comparison to an average cost of $2300 for an individual 25-44 years of age. Over 30% of the total economic cost of falls in the older general population in the United Kingdom is attributed to falls preceded by slips [11].

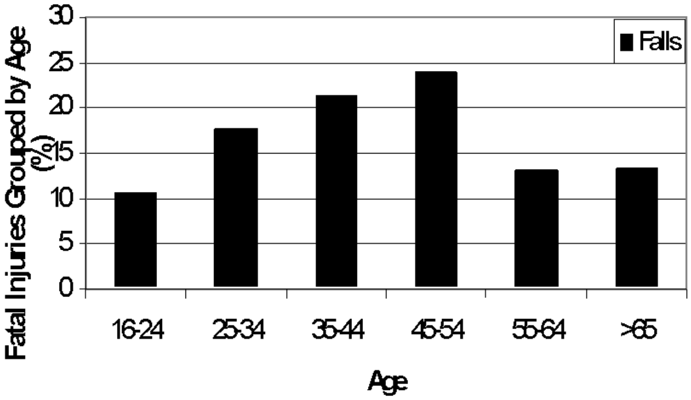

Figure 3: Age Distribution of Work-related falls, 2001 [2].

The aging trend of the population coupled with the predisposition of the elderly to fall is expected to emphasize the seriousness of fall-related concerns. Looking ahead into the future, an approximate 5% increase in the US population of workers aged 55 and older is projected during the 1998-2008 decade compared to the previous decade [13]. In this 98-08 decade, this age group will comprise about 16% of the total labor force [13]. In terms of cost, over $85.37 billion dollars in 2020 due to workplace fall injuries and deaths are anticipated, with more than 37% of this cost attributed to falls among workers over 65 years old [14].

In summary, epidemiological findings indicated that slip-precipitated falls are among the leading causes of injuries and source of high economic costs, especially among older adults. Understanding the biomechanical factors responsible for slipping and falling is an important component in injury prevention [15]. This thesis project focuses on the impact of age and anticipatory postural responses on COM dynamics during slipping. The knowledge gained from this research may provide underlying biomechanical reasons for the epidemiology findings summarized in this section.

1.2 SLIPS AND FALLS

When an individual slips, a postural response is generated to regain balance. These complex recovery mechanisms take place at several body joints (knee, hip, upper extremities, etc) in order to restore perturbed balance. Although research which focuses upon the reactions of individual joints of the body gives insights into the role of that specific joint [15, 16, 17, 18] or on specific characteristics of slips e.g. foot dynamics [19, 15, 17, 20], it does not provide an overall picture of the body's response to a perturbation. This study focuses on potential associations between the three-dimensional dynamics of the body's COM and resulting slipping severity.

1.2.1 Biomechanics of Slips and Falls

The causes of slips and falls involve complex interactions of human and environmental factors [21]. Human factors include gait biomechanics, proprioceptive abilities, aging, perceptual knowledge of a slippery surface, and neuromuscular mechanisms involved in balance and gait. Environmental factors include friction between the foot-floor interface, footwear material, lighting, and floor unevenness. Previous studies focusing on the interactions between human and environmental factors revealed that a slip occurs when the coefficient of friction of the shoe-floor interface does not meet the biomechanical frictional requirements determined by the peak shear-to-normal ground reaction forces, also called peak required coefficient of friction (RCOF), recorded during stance shortly after heel contact [22].

After a slip occurs, the body must initiate a corrective response to regain balance, maintain posture, and continue with forward locomotion. Characterizing biomechanical factors that influence the outcome of a slip lead to a greater understanding of the variables which impacts the ability to recover equilibrium. In an attempt to understand these variables, researchers have exposed participants to moving floor surfaces e.g. simulated slips [16] or to very slippery (contaminated) floors [23, 24, 17, 20, 18]. Most research has focused on postural strategies adopted by the lower body. Findings related to the foot dynamics of the slipping leg indicate that the foot's slipping distance and velocity are positively associated with the risk of falling [16, 17, 20]. Investigators have also noted that corrective reactions generated at the knee and hip of the leading (slipping) leg play a predominant role in balance recovery [25, 17, 15, 18]. More recently, trailing (non-slipping) limb strategies have been underlined in the literature [26] and in some current/preliminary work, including swing phase interruption and thus increase of the base of support (BOS) area. Few other studies have presented evidence of definitive upper body postural strategies, namely an arm elevation strategy, which may influence the outcome of a slip [26]. In summary, the reactions generated during slipping involve intertwined responses generated at several body joints.

The prevalence of falls in the elderly and aging of the population has stimulated research on the differences in the biomechanics of slips between young and older adults. Older people characteristically walk with a shorter stride length, a larger step width, and slower gait speed [23]. These factors should result in a safer or more stable gait; however the epidemiological findings are not in support of this argument. Other factors that may degrade the ability of older adults to recover once a slip is initiated include decreased strength [27] and delayed reaction time [24]. In other words, the typically reduced muscular leg strength found in older adults may prevent the generation of appropriate corrective torques necessary to recover from a slipping perturbation, or alternatively, older adults may react too slowly to stop the sliding motion of the foot. Delayed reaction time may also be due to aging-related proprioceptive deficits that may influence the ability to recognize a slip is occurring.

1.2.2 COM Dynamics When Balance is Perturbed

The human body has a wide range of biomechanical responses, both conscious and reflexive, available to maintain stability during slips and to protect in case of a fall [15]. These multivariate responses include arm elevation, hip and knee motion, trunk motion, and compensatory stepping [15]. The interactions between these responses are complex and their individual impact on balance during walking is difficult to evaluate. Examining the center of mass dynamics during slipping can provide insights into the overall appropriateness of postural responses generated in an attempt to prevent a fall.

Both experimental [26, 28, 23] and modeling [29, 30] studies have examined COM dynamics in response to an external perturbation. Two experimental perturbation paradigms have been used to investigate the COM dynamics during slipping: base of support (BOS) translations simulating slips [26] and gait on contaminated slippery floors [23, 24, 28]. The study by Marigold and Patla investigated the impact of prior knowledge regarding a known forward BOS translation on the COM trajectory [26]. The authors reported that during known perturbations COM-related adaptations were evident compared to findings in unexpected perturbations (e.g. COM was positioned closer to the contralateral (non-perturbed) limb at time of heel contact) [26]. The dynamics of the arms were not included in the computation of the COM position [26], which may significantly impact the findings [15]. Another study by You and colleagues investigated the effect of slippery perturbations on the body's COM for a known slip condition [28]. During falls, participants were unable to bring the COM over the perturbed foot.

Investigations by Lockhart have examined the relationship between aging, RCOF, and the anterior posterior COM velocity [23]. Lockhart found that older adults fell more than their younger counterparts. Additionally, the anterior posterior COM velocity was higher after heel contact in comparison to before heel contact during a slipping perturbation for both young and older adults. This indicates that increasing the anterior posterior COM velocity is an important strategy in slip-recovery reactions. The investigators concluded that COM dynamics is a crucial component necessary to understand the reaction of the whole body in response to a slipping perturbation.

In a 2-D inverted pendulum model of the body during stance, Pai and Patton simulated anterior COM pushes while maintaining a stationary base of support (BOS) in an effort to derive a "stability region" within which loss of balance can be prevented [29]. The model predicted that the initial position of the COM with respect to the BOS plays an important role in determining the boundaries of this stability region. For example, in response to an anterior COM push with a given velocity, a posteriorly positioned COM at the start of the perturbation will increase the chances of recovering balance, i.e. the COM will come to a stop over the BOS as the velocity dissipates. The first modeling study by Pai and Patton [29] was followed by a second inverted pendulum model investigation using a dynamic base of support to simulate a slip [30]. In contrast to the COM's anterior pushes employed in the first study, the model predicted that in order to stay within the stability region in response to a simulated slip (anterior translation of the BOS), an anteriorly positioned COM as well as an increased COM anterior velocity are desired. The investigators hypothesized that subjects adjust their COM initial conditions in anticipation to a known slipping perturbation [30]. The limitations of the studies by Pai and colleagues [29, 30] include the simplicity of the inverted pendulum model (knee and hip reactions are important in large perturbations). Furthermore, COM dynamics were not investigated in the frontal and transverse planes.

Based on previous studies, one of the main goals of corrective reactions generated in response to a slip is to bring the center of mass over the base of support. The 3-D COM dynamics during slipping are yet to be fully described as well as their dependence on aging and anticipatory responses. Thus, this proposed thesis work focuses on these aspects of slips and falls.

2.0 SPECIFIC AIMS

The goal of this research was to gain a greater understanding of the body's center of mass (COM) dynamics during slipping in young and older adults. It is believed that individuals attempt to control the COM to prevent falls during perturbed gait. Thus, the dynamics of the body's COM during slips reveal insights into the biomechanical reasons behind the high prevalence of slip-precipitated falls in the elderly. In addition, tracking COM dynamics during slips is helpful in differentiating between postural strategies that successfully recover balance and responses that result in falls. Previous findings by our research group suggested that the perception of the danger of slipping induces anticipatory responses that are effective in preventing large slipping perturbations. Thus, this project (1) examined differences in COM dynamics between slip-recovery and slip-fall outcomes, (2) investigated the impact of anticipatory responses on COM dynamics, and (3) compared COM dynamics between young and older adults.

2.1 SPECIFIC AIM 1 (SA1)

The first specific aim is to investigate potential associations between the COM dynamics (position and velocity) evaluated at heel contact and the severity of the slip.

H.1) Maintaining the COM closer to the trailing (non-slipping) leg at heel contact will be associated with reductions in slipping distance and velocity (i.e. slip severity), and thus increasing chance of recovery.

H.2) A greater forward velocity of the COM at the time heel contact onto the slippery surface will be associated with reductions in slip severity.

H.3) The COM dynamics at heel contact will have a greater impact on slipping distance/velocity in the elderly compared to the findings in young adults.

2.2 SPECIFIC AIM 2 (SA2)

The second specific aim is to examine the impact of anticipating slippery surfaces on COM dynamics.

H.1) Anticipation conditions will impact COM dynamics at heel contact.

H.2) In the case of a slip, anticipation conditions will be associated with a faster recovery of the COM trajectory. Recovery time will be chosen as the time at which the anterior-posterior distance between the COM and heel of the leading (slipping) leg is zero.

H.3) Anticipation condition will impact COM dynamics to a greater degree in older adults.

In summary, this study investigates the relationship between COM kinematics and slipping severity, as well as the impact of aging on this relationship.

3.0 METHODS

Data for the completion of this research thesis has been collected as part of a larger study funded by the National Institute of Occupational Safety and Health (R03 OH007533, Principal Investigator: Rakié Cham).

3.1 SUBJECTS

The study involved 16 healthy young adult subjects aged between 20 to 35 years and 11 older adult subjects between the ages of 55 to 70 years (Table 1 and Table 2). Prior to testing in the study, a 30-minute neurological screening was required of all subjects. Exclusionary criteria included a history of neurological, orthopedic, vestibular, and any other difficulties that would hinder normal gait. The subjects were required to return for two visits. The first visit is a 30-minute neurological and balance screening while the second visit is the gait testing session. During the gait session, subjects were equipped with a safety harness to prevent them from hitting the ground in case of an irrecoverable balance loss. This harness has been used in previous research and has proven to be safe without impeding natural walking. The age, weight, stature, and gender of all subjects are detailed in Table 1 and Table 2.

Table 1: Gender Distribution

	Young(N)	Older (N)
Female	9	7
Male	7	4
Total	16	11

Table 2: Subject Population Characteristics

	Young Mean (SD) [Range]	Older Mean (SD) [Range]
Age (yrs)	23.5 (3.2) [20-33]	60.9 (4.0) [55-67]
Weight (kg)	67.6 (10.5) [53-89]	78.2 (10.9) [56-93]
Stature (cm)	171.2 (8.9) [159-194]	166.2 (8.1) [154-179]

3.2 EQUIPMENT

Data collection of gait variables were synchronized and sampled at 1080 Hz, with the kinematic data sampled at 120 Hz. These variables included ground reaction forces recorded under each foot individually (2 BERTEC 4060 force platforms) and body motions from 79 VICON passive markers (8 M2-camera VICON system 612) attached to the body and shoes (Figure 4, Table 3). Eight Vicon cameras were placed around the lab to setup a capture volume of dimensions approximately 6.6 x 2 x 2 m on top of the force plates for 3D motion analysis (Figure 5). An overhead harness system coupled with an overhead pulley was used to catch the participant in the event of an irrecoverable balance loss.

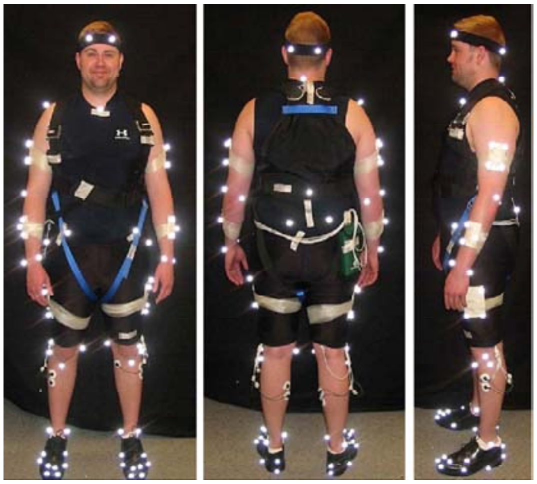

Figure 4: Marker placement on the body

Table 3: Segments and position of Vicon markers

Segment	Position of markers
Head	2 markers on the frontal bone (forehead) and 2 markers on the parietal bone (posterior)
Torso	L/R acromium, cervical vertebra 7, sternum, thoracic vertebra 10[c]
Upper arm (L/R)	Cluster of 4 markers attached mid-segment, lateral[c] and medial[c] epicondyli of humerus
Forearm (L/R)	Cluster of 3 markers attached mid-segment, lateral[c] and medial[c] styloid processes (wrist)
Pelvis	L/R anterior superior iliac spines (ASIS) and left/right posterior superior iliac spines (PSIS)
Thigh (L/R)	Cluster of 4 markers, lateral and medial[c] femoral epicondyli, greater trochanter[c]
Shank (L/R)	Fibula head, tibial tuberosity, lateral and medial malleoli
Forefoot (L/R)	4 markers surrounding anterior side of shoe (distal phalanges)
Hindfoot (L/R)	4 markers surrounding posterior side of shoe (tarsals/metatarsals), heel[c], lateral[c] and medial[c] sides of flexion-extension axis of metatarsals/phalanges joint

L/R =Left/Right

[c] = Marker present only in standing calibration trial and reconstructed in the gait trials based on its 3D-relationship with other markers belonging to the same segment and present in the dynamic trials.

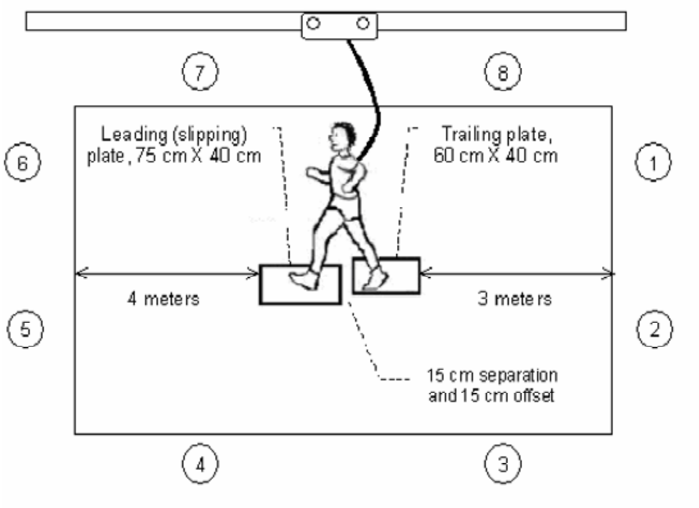

Figure 5: Experimental Laboratory Setup

3.3 CONDITIONS AND PROTOCOL

All participants were instructed to follow the same walking protocol. First, written informed consent approved by the Institutional Review Board of the University of Pittsburgh was obtained. The subject was then instrumented with the markers and equipped with safety harness. Subjects were instructed to walk at a self chosen speed and allowed to practice such that each foot hit one and only one force platform embedded into the ground such that the participant's left foot landed onto the flooring area that would be contaminated during the slippery conditions. Prior to every trial, the subject was instructed to face away from the walkway and listen to loud music for one minute, which distracted the participant in the case that glycerol was applied onto the floor. After one minute, the subject was instructed to turn around and walk to the end of the runway while data were recorded by the motion capture system. To generate slip events a diluted glycerol solution, 75% glycerol by volume, was applied uniformly onto the force platform in a location such that the left foot made contact with the slippery area, while the right leg was the trailing limb.

The conditions included in the testing were as follows:

- "Known Dry" trial: The subject was informed that the first few trials will be dry, ensuring natural walking with no fear of slipping. At least two known dry trials were collected.
- "Unexpected" warning condition: No information about the floor's contaminant condition was given to the subject. The third trial was the unexpected slip.
- "Alert" warning conditions: The subject was verbally warned of the possibility of encountering slippery floors prior to each trial. Four dry trials were collected followed by a glycerol-contaminated condition, and four dry trials were presented after. In this thesis the dry trials collected after the alert contaminated condition were not included in the analysis.
- "Known Slip" warning condition: The subject was informed of the floor's slippery condition and instructed to walk across the contaminated floor and do his/her best to prevent falling.

3.4 WHOLE BODY MODEL

A whole body model was generated consisting of 13 rigid segments: The foot, shank, thigh, forearm, and upper arm for each side of the body, as well as the pelvis, torso and head. A 3D 13-segment (Table 3, Figure 6, and Figure 7) whole-body model was built in Body Builder (version 3.55, Vicon Motion Systems) as part of ongoing gait investigations. Segmental mass and inertial properties are based on data published by Chandler [31]. A total of 79 markers was used, 60 dynamic and 19 static. Static markers were removed for dynamic trials because of their increased likelihood of being blocked or knocked off the body during a slip. The static markers were reconstructed from dynamic trials by finding its position within the static local coordinate system of the foot. For dynamic trials this point was reconstructed within the dynamic local coordinate system using the derived static coordinates.

The wrist, elbow, ankle and knee joint centers were taken as the midpoint between the lateral and medial styloid processes, epicondyli of the humerus, malleoli, and femoral epicondyli, respectively. The shoulder joint center was derived from the acromium marker [32], while the hip joint center was based on Bell's regression equation [33, 34]. Segment lengths were derived from a standing calibration trial using the distance between relevant joint centers. The orientation of the lower extremities' local coordinate systems followed the convention proposed by Cappozzo [35], while local axes of the upper body's segments adhere to the suggestions of Roux [36] and Schmidt [32].

The relative orientation between neighboring segments was computed based on the widely used convention of Grood and Suntay [37] and recommended in the standards of the International Society of Biomechanics [38]. A segmental analysis was used to compute the COM position in this study, i.e. the body's COM was calculated using Equation 1 [39]:

$$COM_a = \frac{\sum m_i a_i}{\sum m_i} \qquad \textbf{(1)}$$

where m is the mass of each segment i and a is the global coordinate of interest.

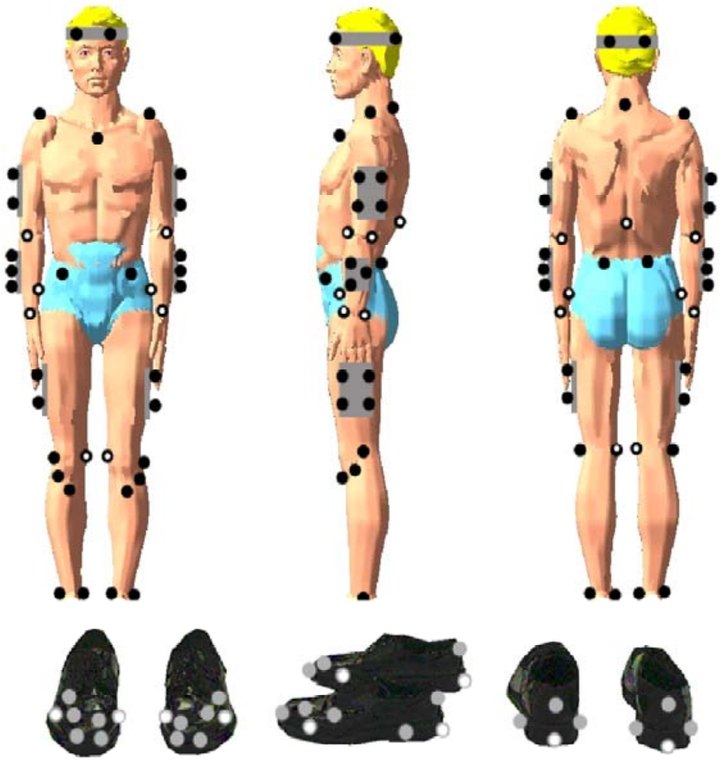

Figure 6: Marker placement on the body. The static markers are the hollow markers while dynamic markers are solid. The markers on the shoes (N=22) have a 9.5 mm diameter, while the rest of the markers on the body are 14 mm in diameter.

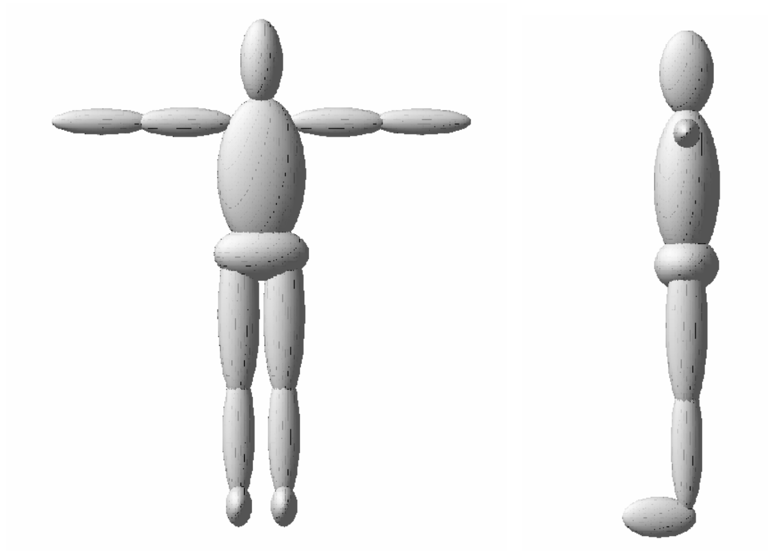

Figure 7: Segment divisions of the body

3.5 DATA PROCESSING

3.5.1 Overview

This Master's Thesis project focused on the COM position, COM velocity and the severity of the slip based on the peak slipping velocity (PSV) of the left heel. Normal ground reaction forces were used to identify heel contact (HC) and toe off (TO) frames of the left (slipping) foot. Stance time, defined between HC and TO, was used to time normalize the gait data collected on dry surfaces. For slippery trials, stance time of the dry trial prior to the slip was used to normalize the data.

Regarding the filtration of data, there are two possible sources of internal filtering within the Vicon motion analysis system. If a marker went missing during the course of a trial, during data processing a cubic spline interpolation was employed to estimate the location of missing data points in addition to a moving average to estimate any remaining missing markers. Since the algorithm used to arrive at this point is proprietary to Vicon, the data hereafter shall be referred to as 'unfiltered' in order to clarify the data process.

3.5.2 Slip Severity/Left Heel Data

The unfiltered 3D instantaneous position of the reconstructed left heel marker (Figure 8) was numerically differentiated to derive heel velocity information (Figure 9). The resultant (medial-lateral and anterior-posterior) transverse plane heel velocity was calculated and a customized MATLAB routine was used to identify the time of PSV between HC time and the end of the slip (EOS). Peak slip velocity (PSV) was identified as the first local maximum occurring in the resultant velocity after 50 ms from heel strike. The EOS frame was selected either as the time of recovery (i.e. heel velocity returned to 0 baseline), or in the case of a fall (subject fell into the harness or slipped beyond the capture volume) the EOS was set to the time of the typical second peak that occurs in the anterior-posterior heel velocity time series HC (Figure 9, B). Total slip distance (TSD) was also measured as a secondary measure of slip severity. Specifically, TSD was assessed as the resultant distance (medial-lateral and anterior-posterior) traveled along the floor by the left heel marker between HC time and EOS, as illustrated in Figure 8.

Each slip trial was classified as hazardous or non-hazardous. This classification was based on the value of PSV. More specifically, a slip trial was classified as hazardous if the resultant PSV was greater or equal to 1 m/s. The slip trial was labeled as non hazardous if this PSV cutoff criterion was not satisfied. It should be noted that in the case of a hazardous slip, TSD is probably a conservative value as the subject often slipped beyond the capture volume or fell into the harness. This is the reason for the choice of PSV as a primary measure of slip severity.

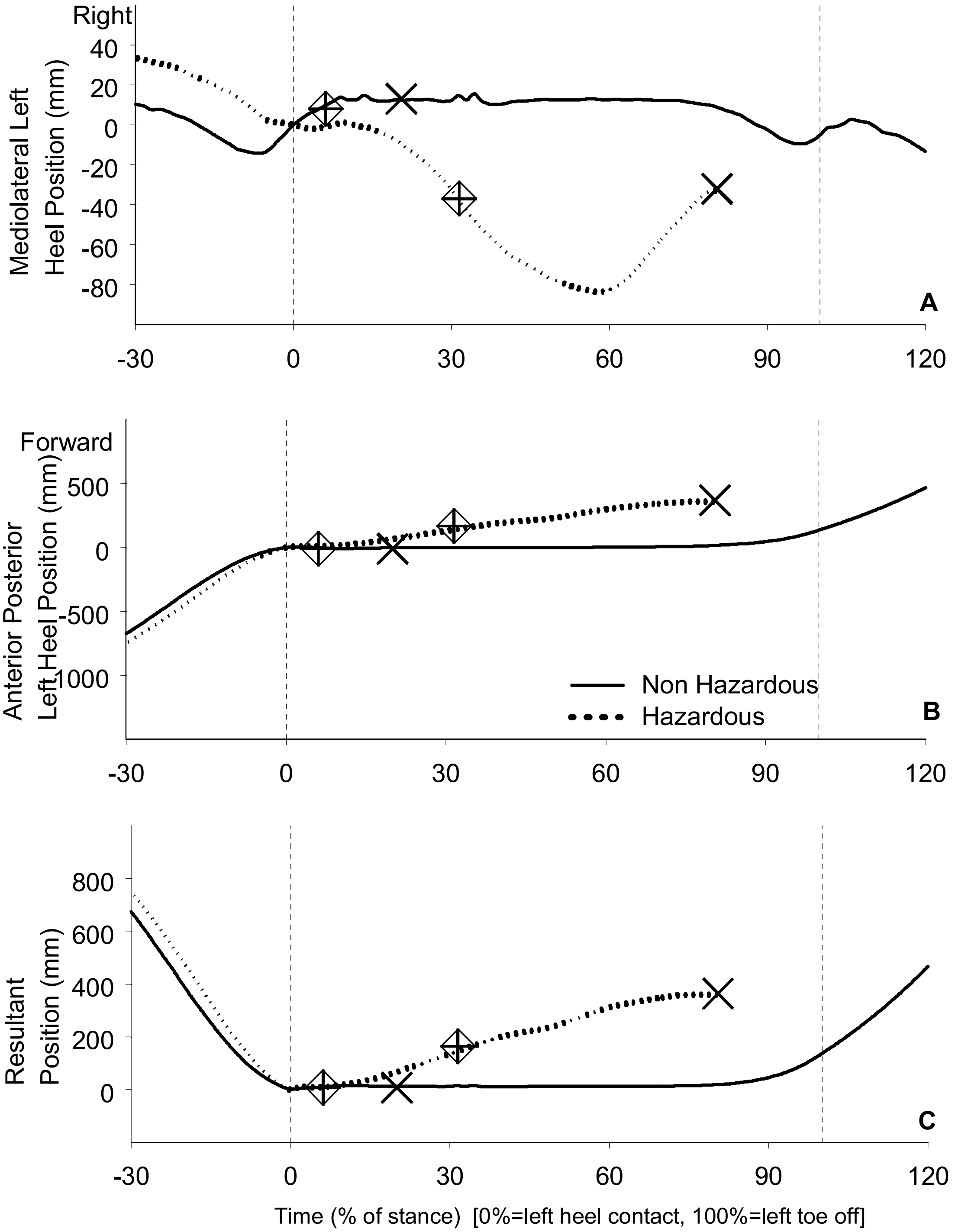

Figure 8: Distance traveled by the slipping foot (C) in global coordinates calculated as the resultant of the dimensions of the transverse plane of the floor (A and B) for both Non-Hazardous and Hazardous slip outcomes. An X denotes the EOS while a diamond marks time of PSV. These events were set based on the heel velocity data (Figure 9)

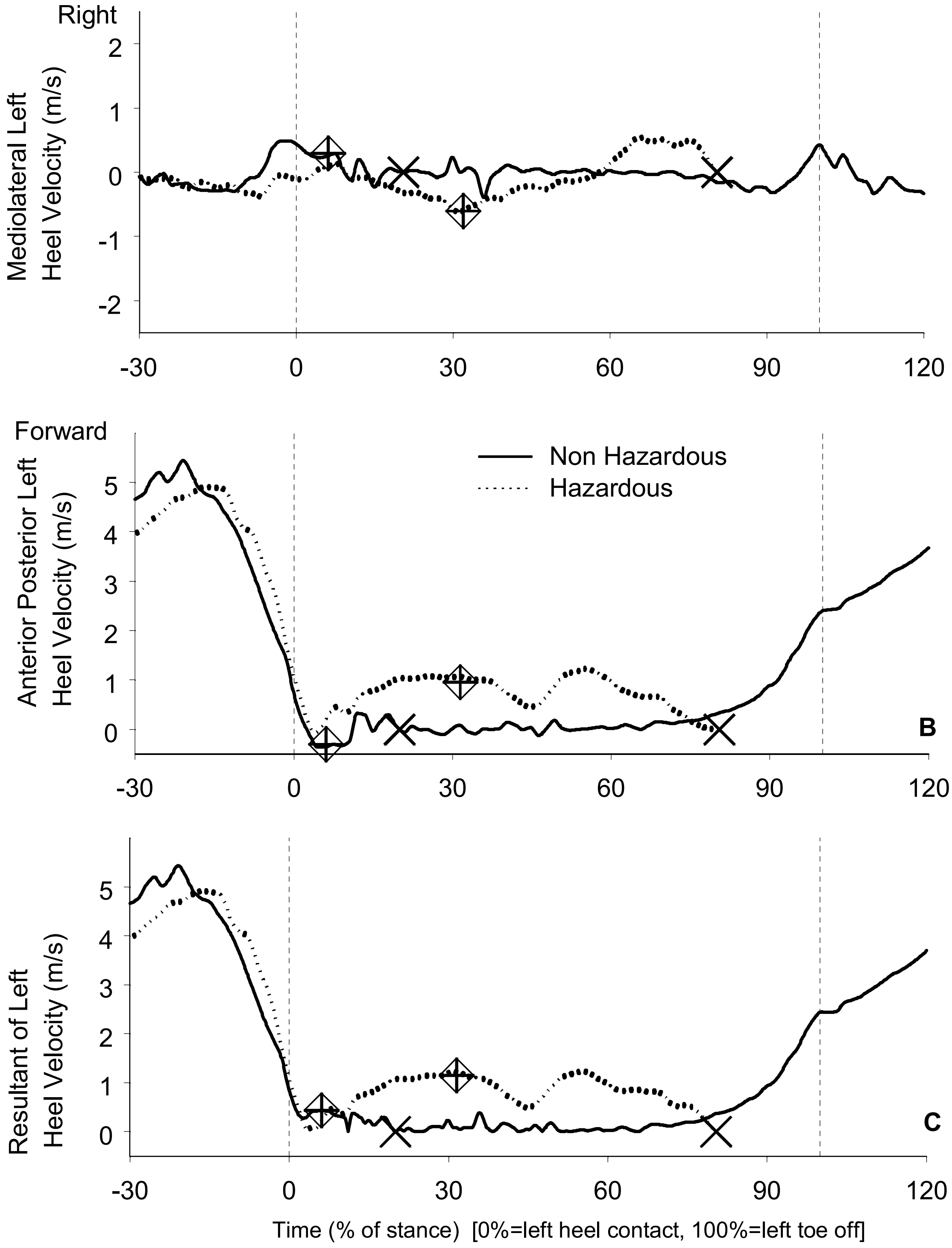

Figure 9: Unfiltered velocity of the slipping foot (C) calculated as the resultant of the dimensions of the transverse plane of the floor (A and B) for both Non-Hazardous and Hazardous slip outcomes. An X denotes the EOS while a diamond marks time of PSV.

3.5.3 COM related variables

The Cartesian COM coordinates, i.e. medial-lateral (ML COM), anterior-posterior (AP COM), and vertical COM position (UP COM) were calculated relative to the position of the left heel (leading foot) at time of HC (typical time trajectory represented in Figure 10 for a dry baseline trial). Furthermore, the vertical COM (UP COM) was normalized to stature to account for differences in height within the subject population. The 3D components of the COM position were filtered using a 10 Hz lowpass elliptical filter and numerically differentiated to derive the COM velocity information (VML COM, VAP COM, and VUP COM as typically represented in Figure 11). The typical time trajectory of the COM kinematics (Cartesian position, velocity) represented in Figures 10-11 for a baseline dry trial indicates agreement with previously published data [40, 41].

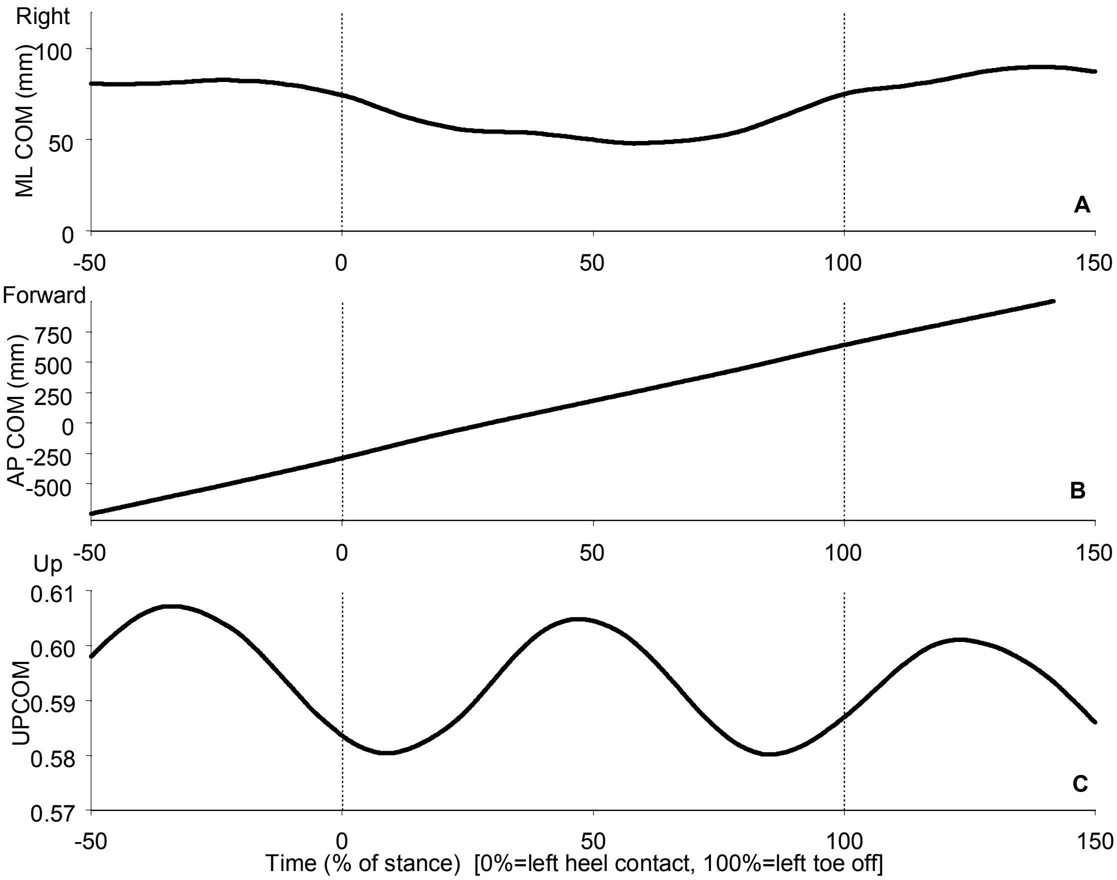

Figure 10: Typical Cartesian based position graphs of a young female subject. Positive values indicate right, forward, and up for the mediolateral (ML COM), anterior posterior (AP COM), and vertical COM (UP COM) respectively. Lines indicate HC and TO.

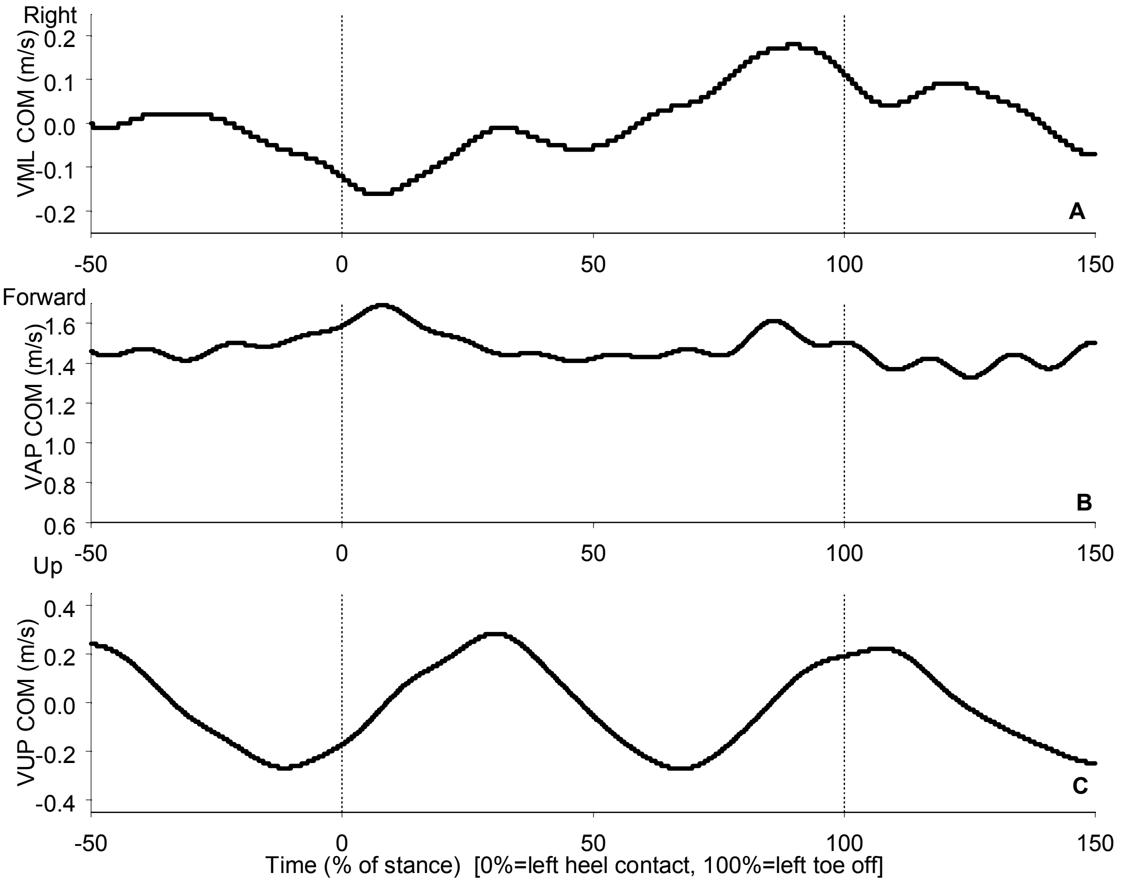

Figure 11: Typical Cartesian based velocity graphs of a young female subject. Positive values indicate the COM is moving toward the right, forward, and top sides of the body for the mediolateral (VML COM), anterior posterior (VAP COM), and vertical (VUP COM) COM velocity respectively. Lines indicate HC and TO.

The COM position was converted from a Cartesian coordinate system to cylindrical coordinates in order to provide the resultant distance (DCOM) and orientation (ORCOM) of the COM relative to the left heel at HC in the horizontal plane in order to observe an overall COM position component. Specifically, DCOM was calculated as the square root of the sum of squares of the mediolateral (ML COM) and anterior posterior (AP COM) position (Figure 12 represents a typical DCOM time series). Furthermore, the DCOM was normalized to stature to account for the impact of differences in height within the subject population on the COM placement. The orientation of the COM in the transverse plane (ORCOM) was calculated as explicitly stated in Equation 2. That is, the global orientation of the vector COM-Left heel is calculated in the transverse plane and normalized to a direction of travel (in case the subject were not walking in a straight line). The direction of travel is arbitrarily set to the orientation of the COM trajectory between HC and the normalized time -30% of stance. Figure 12 represents a typical DCOM and ORCOM time series. The DCOM (Figure 12, A) decreases linearly, since the COM is behind the left foot. After the COM progresses over the left heel, it increases linearly. The ORCOM is 0 degrees as the COM approaches the left heel. As the COM progresses over the heel, it flips 180 degrees.

$$ORCOM = \frac{180}{\pi}\left[\arctan\left(\frac{MLCOM_{HC}}{APCOM_{HC}}\right) - \arctan\left(\frac{MLCOM_{-30\%} - MLCOM_{HC}}{APCOM_{-30\%} - APCOM_{HC}}\right)\right] \quad \textbf{(2)}$$

Where, ORCOM is the orientation of the COM with respect to the left heel at HC in the horizontal plane,
ML COM_{HC}*, is the mediolateral COM at time of heel contact,*
AP COM_{HC}*, is the anterior posterior COM at time of heel contact*
ML $COM_{-30\%}$*, is the mediolateral COM at -30% of stance phase, and*
AP $COM_{-30\%}$*, is the anterior posterior COM at -30% of stance phase.*

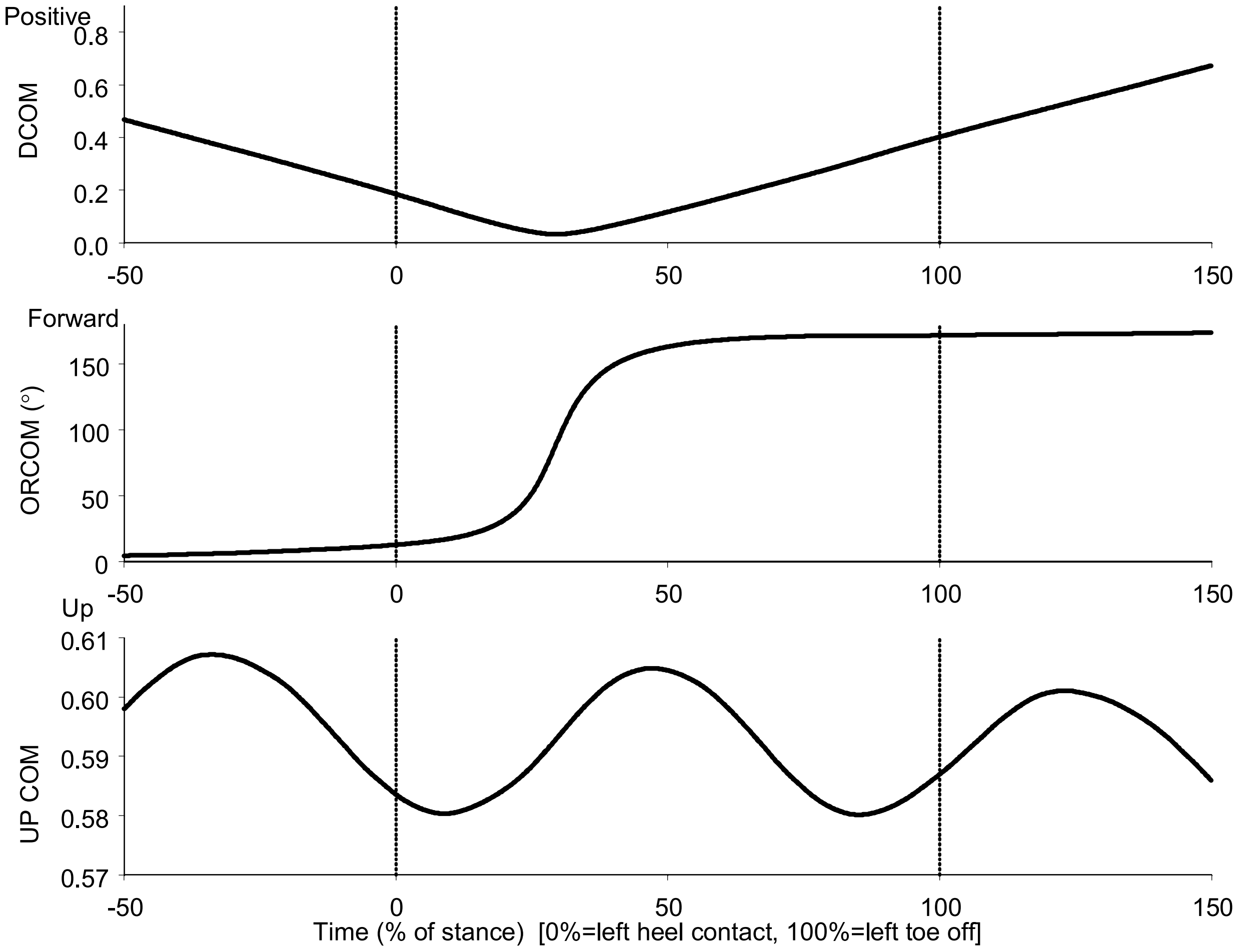

Figure 12: Typical cylindrical based position graphs of a young female subject. A positive DCOM indicates greater distance from the left heel. The ORCOM begins at zero and grows increasingly positive as the subject passes over the left heel. The UP COM is more positive closer to the head. Lines indicate HC and TO. (DCOM and UPCOM are normalized with respect to stature)

3.5.4 Additional relevant variables

Other calculations relevant to the Master's Thesis project are gait speed, step width, and step length. Gait speed (GS) was computed as the total anterior posterior distance traveled by the COM between left and right heel strikes divided by the travel time. Step width (SW) was determined to be the distance in the frontal plane between the right and left heel markers at time of HC. Step length was computed to be the distance in the sagittal plane between the right and left heel markers at time of HC. Step Width and Step Length were normalized to left leg length in order to account for differences in anthropometry.

3.6 DATA ANALYSIS

To analyze the Specific Aims, point in time values of the dynamic variables listed in Table 4 were calculated for each trial. Times of interest were HC (SA1, SA2) and an average reaction time of 200 ms after HC (SA2). For both Specific Aim data sets, the normality of all variables was checked and an outlier analysis using the jackknife distance method was performed on the relevant variables pertaining to the specific hypotheses. Any subject data identified as an outlier was removed from further analysis and summary. Analysis of variance (ANOVA) conducted on the gait variables listed in Table 4 were used to test the hypotheses associated with the Specific Aims with a significant level of 0.05 used to determine significance. In addition, the baseline dry trial used for comparison in the statistical analysis was the first dry trial preceding the slip.

Table 4: Dependent Gait Variables

COM-related variables	**Foot kinematics *(leading leg)***	**Other**
3D COM position[§]	Heel slip distance	Slip outcome[£]
3D COM velocity	Heel slip velocity	

[§] The COM position is taken relative to the left (leading leg) heel taken at the time of HC.
[£] Each slip will be classified as hazardous or non-hazardous slip.

Specific Aim 1 will investigate potential associations between aging and COM dynamics evaluated at heel contact and the severity of the slip as well as the corrective reactions employed in an attempt to prevent falling.

Only unexpected slippery trials for both the young and old, male and female subjects were included in the analyses associated with the testing of the hypotheses of Specific Aim #1.

H.1 ***Maintaining the COM closer to the trailing (non-slipping) leg at heel contact will be associated with reductions in slipping velocity, and thus increasing chance of recovery.***

H.2 ***A greater forward velocity of the COM at the time heel contact onto the slippery surface will be associated with reductions in slip severity.***

H.3 ***The COM dynamics at heel contact will have a greater impact on slipping distance/velocity in the elderly compared to the findings in young adults.***

Two four-factor ANOVAs were conducted on slip velocity measured at the left heel for the unexpected slip trials (Table 4). The three factors are the 3-D components of the COM position (H.1) and velocity (H.2) evaluated at the time of left HC. The fourth factor was age group, included as a between-subject effect in the ANOVA (H.3). A significant COM dynamics factor ($p<0.05$) would be indicative of a non-negligible association between the slip severity (slip velocity) and the specific aspect of the COM dynamics under investigation.

In order to compare COM dynamics between the possible outcomes of slipping, a series of logistic regressions were conducted on the variables describing the COM dynamics at time of HC (H.1., H.2.) with age group included as a between-subject effect (H.3) for the unexpected slip trials against the outcome of the slip (hazardous, non-hazardous). A significant level of 0.05

was followed by post-hoc pairwise testing to investigate specific differences in COM dynamics between the three outcomes.

Specific Aim 2 will examine the impact of anticipating slippery surfaces on the dynamics of the COM.

Both the young and old, male and female data will be included in the analyses associated with the testing of aim 2's hypotheses.

H.1 Anticipation conditions will impact COM dynamics.

H.2 In the case of a slip, anticipation conditions will be associated with a faster recovery of the COM trajectory. Recovery time will be chosen as the time at which the anterior-posterior distance between the COM and heel of the leading (slipping) leg is zero.

H.3 Anticipation condition will impact COM dynamics to a greater degree in older adults.

H.1 will utilize the dry trials collected under the baseline (known dry) and alert warning conditions. Only the two baseline dry trials preceding the unexpected slip and the two alert dry trials preceding the alert slip condition are selected for this analysis. A series of one factor within-subject ANOVAs were conducted on the COM dynamics (position and velocity) (see Table 4), with the warning condition being the explanatory effect of interest. In addition, age group is included as an additional (between-subject) effect (H.3) as well as the second order interaction effects of warning and age group. The dependent variables will be evaluated at HC and 200 ms after HC. A significant warning factor would be indicative of the participants' abilities to control the body's COM dynamics when a slipping danger is perceived.

The testing of H.2 will include the slippery trials collected under the three warning conditions (unexpected, alert and known). A two factor within-subject ANOVA was conducted on the recovery time of the COM trajectory (quantified as explained in the formulation of H.2), with the independent factor being the warning condition, age group (H.3), and their interaction effect.

4.0 SPECIFIC AIM #1

4.1 QUALITATIVE DESCRIPTION OF GAIT VARIABLES RELATIVE TO SA1

To qualitatively inspect differences in COM trajectories between walking patterns that resulted in a hazardous slip and those that did not, the time history of the COM variables recorded in a typical hazardous slip trial was compared to the average (+/- 1 SE) gait patterns that prevented a hazardous slip outcome (Figures 13-14). Pre-heel contact patterns, i.e. pre-slip patterns, suggest the only variables that differentiated gait patterns at high risk of slips are the DCOM (Figure 13a), UPCOM (Figure 13a), and VML COM (Figure 14a). Specifically, hazardous slip events were characterized by a greater DCOM (i.e. COM closer to the trailing leg), VML (faster medial lateral COM transitions) and UPCOM (elevated COM).

After a slip occurs, i.e. post HC, the data suggests that the goal of a slipping individual is to regain balance by bringing the COM back in line with ‘normal’ gait. The time trajectories of COM variables in hazardous slip trials undergo divergence with ‘normal’ gait, in both position (e.g. vertical COM position in Figure 13C) and velocity (e.g. medial-lateral and vertical COM velocity in Figures 14 AC), approximately 15-20% into stance.

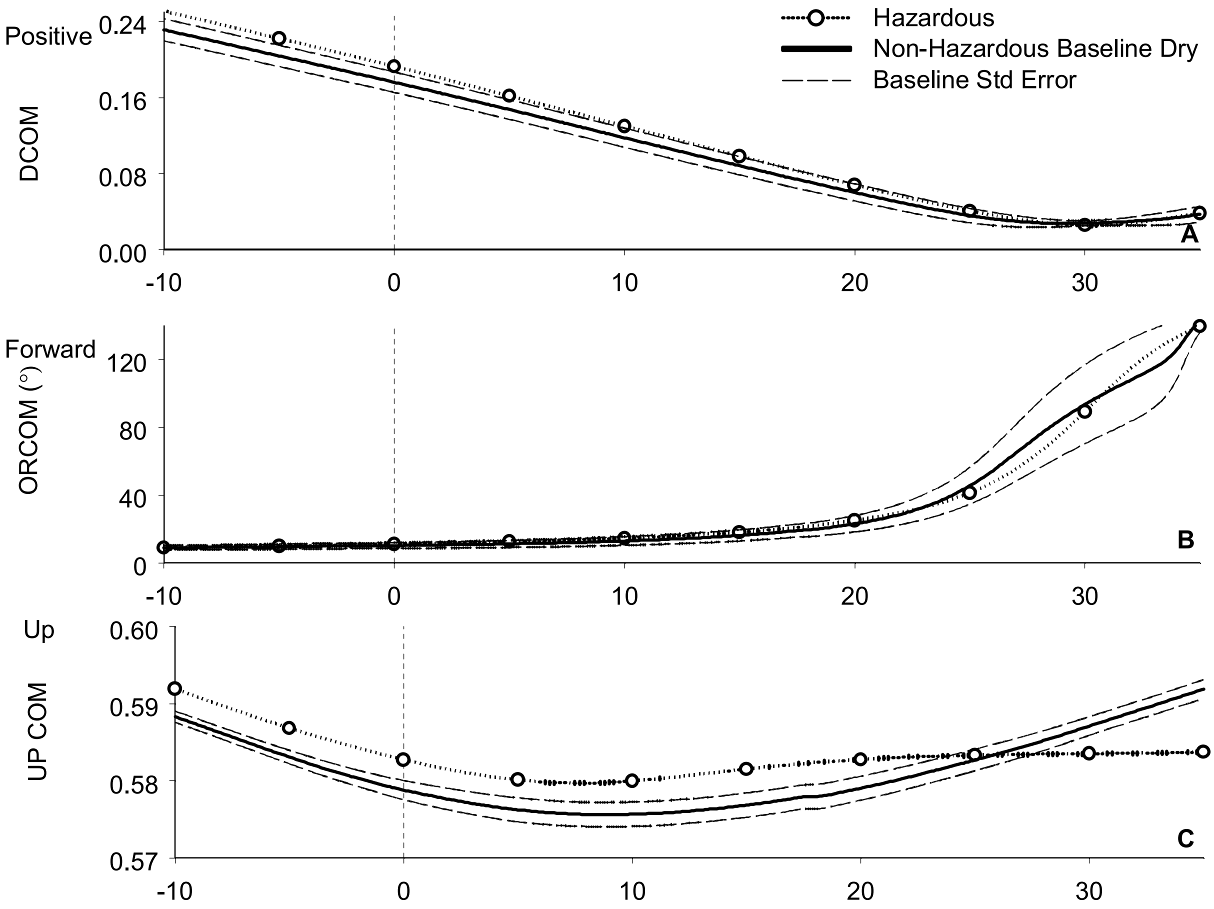

Figure 13: Typical cylindrical based position graphs of the averaged non-hazardous baseline dry trials (mean +/-SE) for all young subjects (black line/gray shading). A hazardous slip outcome of a young individual (hollow circle – dotted line) for the unexpected slip trial is also shown. A positive DCOM indicates greater distance. The ORCOM grows increasingly negative until the subject passes over the left heel. The UP COM is more positive closer to the head. The line indicates HC. (DCOM and UPCOM are normalized with respect to stature).

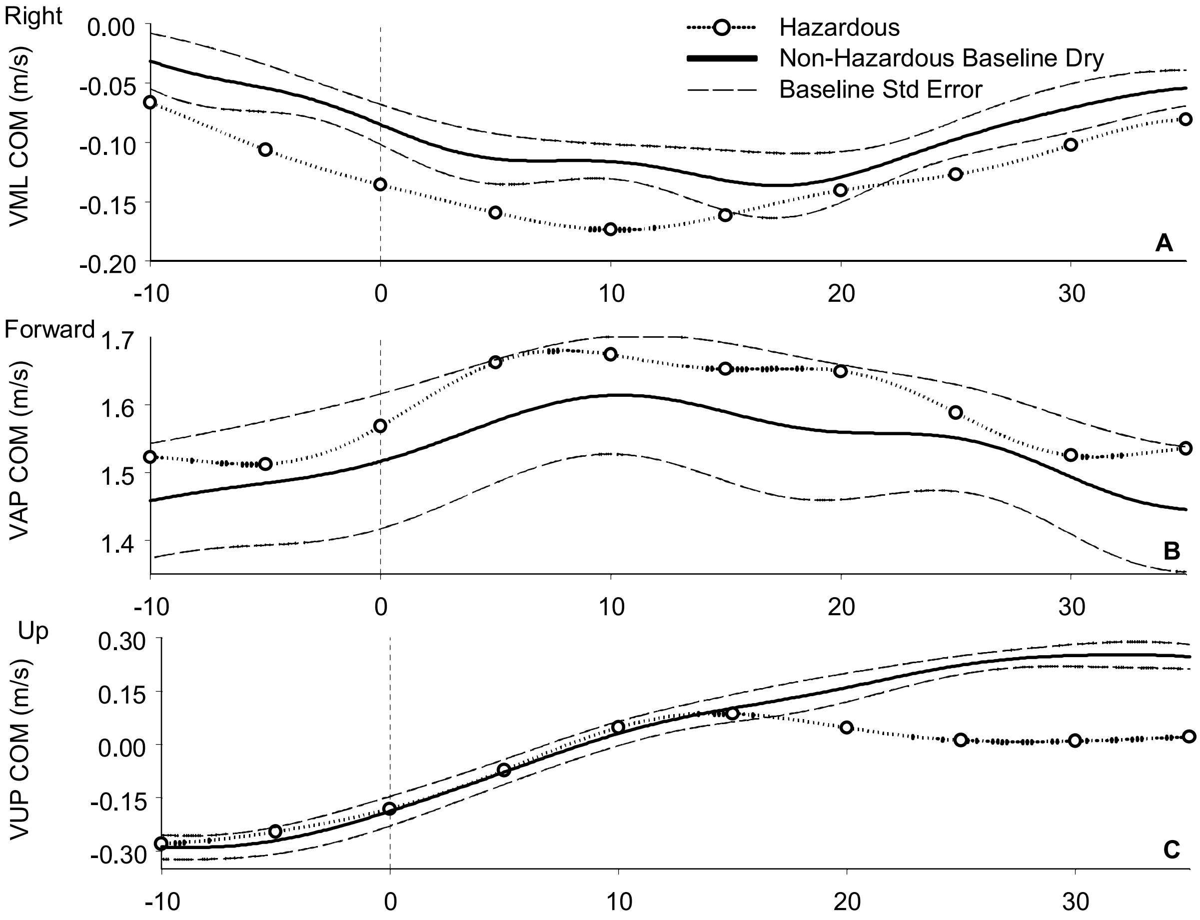

Figure 14: Typical Cartesian based velocity graphs of the averaged non-hazardous baseline dry trials (mean +/-SE) for all young subjects (black line/gray shading). A hazardous slip outcome of a young individual (hollow circle – dotted line) for the unexpected slip trial is also shown. Positive values indicate the COM is moving toward the right, forward, and top sides of the body for the VML COM, VAP COM, and VUP COM respectively. The line indicates HC.

4.2 CORRELATION ANALYSIS

In order to examine Specific Aim #1, only the unexpected slippery trials for both male and female subjects of all ages were included in analyses relative to SA1. A correlation analysis confirmed the expectations that slip distance and slip velocity are highly correlated (Table 5, r = 0.88), thus only slip velocity was used in further analyses due to the more reliable nature of PSV in hazardous slips as previously mentioned in *3.5 DATA* PROCESSING. Several strong correlations include the intuitive relationship between COM components, for example step width (SW) and mediolateral COM velocity (r=-0.64) and gait speed (GS) and anterior posterior COM velocity (r=0.73) which use similar components in their derivations. Other relationships of interest include the orientation of the COM (ORCOM) and step width (0.64) which is highly related due to the mathematical definition of ORCOM. A weak correlation of note is gait speed to total slip distance (TSD) and peak slip velocity (PSV).

Table 5: Correlation Matrix of SA1 Variables (Appendix)

TSD	**PSV**	**SW**	**SL**	**GS**	**DCOM**	**OR COM**	**UP COM**	**VML COM**	**VAP COM**	**VUP COM**
TSD	0.88	0.47	-0.28	-0.07	0.40	0.18	0.44	-0.60	-0.02	0.30
	PSV	0.32	-0.31	-0.08	0.42	0.13	0.41	-0.53	0.00	0.28
		SW	-0.06	-0.12	0.11	0.64	0.17	-0.64	-0.06	0.19
			SL	-0.41	-0.54	0.14	-0.07	0.07	-0.40	0.28
				GS	0.02	0.21	-0.09	0.22	0.73	-0.48
					D COM	-0.30	-0.14	-0.33	0.36	-0.25
						OR COM	0.04	-0.46	-0.12	0.05
							UP COM	-0.20	-0.08	0.24
								VML COM	0.22	-0.42
									VAP COM	-0.44
										VUP COM

4.3 QUANTITATIVE DESCRIPTION OF GAIT VARIABLES RELATIVE TO SA1

Both young and old individuals had similar slip outcomes for the unexpected slip (Table 6) with only a 3.1% difference between the two age groups for each slip outcome.

Table 6: Slip Outcome by Age

	Hazardous	Non-Hazardous
Young	66.7%	33.3%
Old	63.6%	36.4%

T-tests were run to investigate differences in the relevant parameters associated with SA1 (unexpected slips) between young and older adults using a significance level of $p<0.05$ (Table 7). In general, the average slipping perturbation (peak slip velocity), while of a lesser magnitude in the young subjects, was not significantly different between young and older adults. Similarly the average gait speed for younger adults was greater than that of older, but not significantly (GS in Table 7). Finally, only the anterior-posterior COM velocity (VAP COM in Table 7) evaluated at HC showed significant differences between young and older adults. Specifically, VAP COM was significantly greater in young compared to older subjects (~7% difference).

Table 7: Parameters relevant to SA1

Mean (SD)	Young	Older
PSV (m/s)	1.24 (0.50)	1.30 (0.55)
GS (m/s)	1.47 (0.12)	1.38 (0.09)
ML COM (mm)	60.42 (22.14)	56.07 (25.27)
AP COM (mm)	-304 (30)	-275 (24)
UP COM	0.581 (0.004)	0.581 (0.004)
DCOM (mm)	0.18 (0.02)	0.17 (0.02)
ORCOM (°)	10.53 (3.23)	11.11 (3.70)
VML COM (m/s)	0.09 (0.04)	-0.08 (0.05)
VAP COM (m/s)*	1.49 (0.12)	1.38 (1.10)
VUP COM (m/s)	-0.19 (0.05)	-0.18 (0.03)

* = age significance

4.4 HYPOTHESIS TESTING

To test the hypotheses of Specific Aim #1, two four-factor ANOVAs were conducted on PSV for the unexpected slip trials. The four factors are the 3-D components of the COM position (H.1) and velocity (H.2) evaluated at the time of left HC. The fourth factor was age group, included as a between-subject effect in the ANOVA (H.3). As indicated by Table 5, none of the independent variables included in the same ANOVA model are strongly correlated.

The ANOVAs revealed significant relationships between PSV and the independent variables DCOM, UP COM, and VML COM. Specifically, maintaining the COM closer to the leading leg (DCOM) and a relatively lowered COM position (UP COM) (Figure 15) were associated with decreases in PSV. Also, fast medial-lateral COM transfers to the leading/slipping leg (VML COM) (Figure 16) were associated with increases in PSV. Age was not significant in either ANOVA model.

Table 8: COM dynamics and Slip Severity

ANOVA MODEL	Dependent variable	Independent variable	P-value
1	PSV R^2=0.539	DCOM	**0.0012**
		ORCOM	0.0954
		UP COM	**0.0050**
		Age	0.1363
2	PSV R^2=0.536	VML COM	**0.0220**
		VAP COM	0.3202
		VUP COM	0.5459
		Age	0.5038

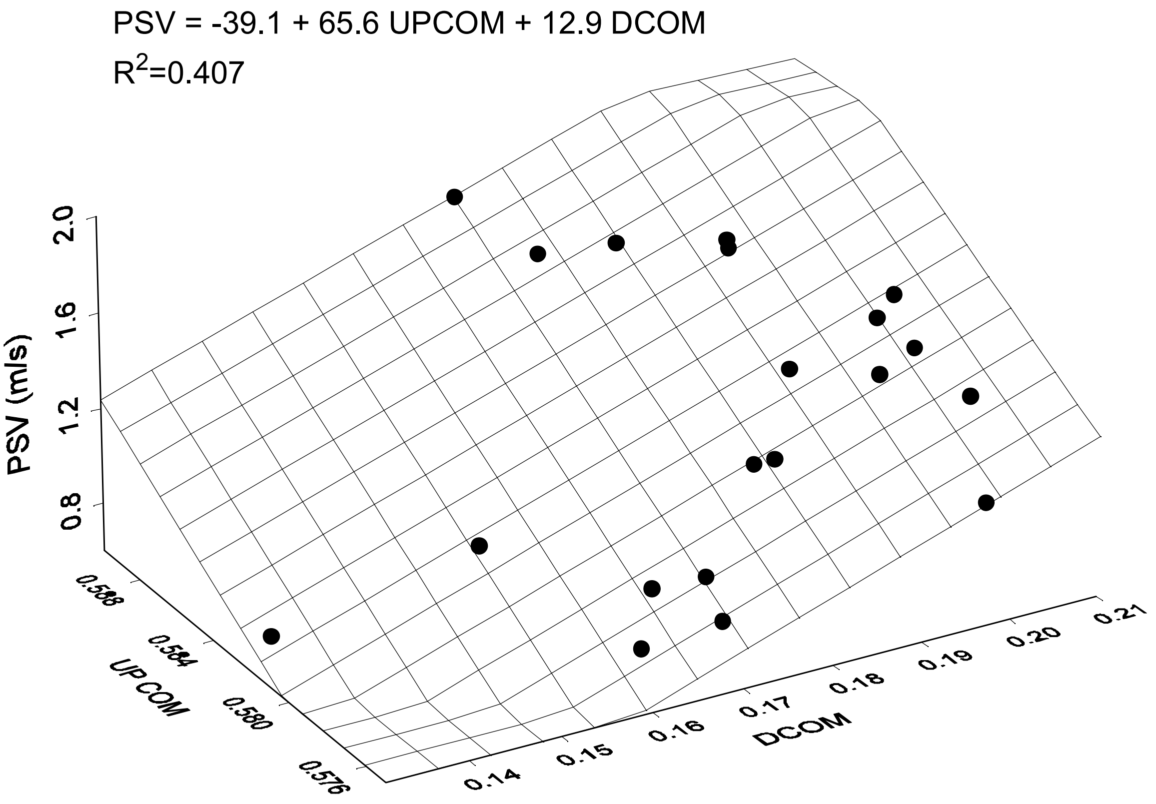

Figure 15: Peak Slip Velocity as a function of this distance of the COM to the left heel in the transverse plane (DCOM) and the vertical COM position (UP COM).

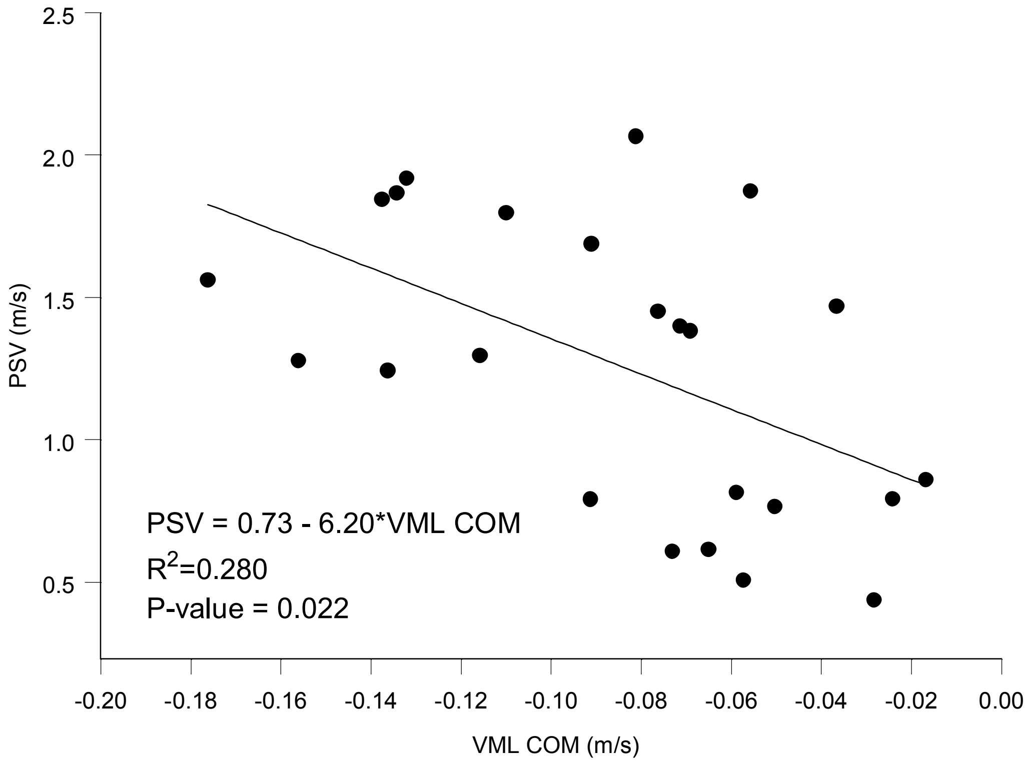

Figure 16: Peak Slip Velocity plotted versus mediolateral COM velocity (VML COM). Age was not significant.

In a further analysis, the significant variables from the previous statistical analyses were combined to conduct an additional four-factor ANOVA to investigate the relative importance of these variables on PSV. This analysis indicates that PSV was mostly affected by DCOM and UP COM (Table 9). The impact of VML COM and age were not significant (There were no significant second-order interaction effects involving age).

Table 9: Combination of Variables

Dependent variable	**Independent variable**	**P value**
Peak Slip Velocity	DCOM	**0.0214**
	VML COM	0.1027
	UP COM	**0.0191**
	Age	0.2097

A logistic regression analysis was performed in an attempt to predict the outcome of slipping (hazardous/non-hazardous) using the COM variables present in previous analyses. The goal is to predict whether a specific COM variable influences the outcome of a slip. A series of logistic regressions were conducted on the variables describing the COM dynamics at time of HC (H.1., H.2.) with age group included as a between-subject effect (H.3.) for the unexpected slip trials against the outcome of the slip (hazardous, non-hazardous). Of the COM position and velocity variables tested, only the distance of the COM to the left heel in the transverse place (DCOM) and the mediolateral COM velocity (VML COM) were significant (Table 10). Age is not significant in any of the regressions. The value of this analysis is in its predictive nature. The DCOM and VML COM had values 18.8% and 120% higher respectively for the hazardous slip outcome in comparison to the non-hazardous outcome.

Table 10: Logistic Regression results

Mean (SD)	Distance of COM to Left Heel	Mediolateral COM Velocity (m/s)
Hazardous	0.19 (0.04)	-0.11 (0.01)
Non-Hazardous	0.16 (0.02)	-0.05 (0.02)

5.0 SPECIFIC AIM #2

5.1 HYPOTHESIS TESTING

Only the two baseline dry trials preceding the unexpected slip and the two alert dry trials preceding the alert slip condition were selected to test H.1. and part of H.3. A series of two factor ANOVAs (Warning and Age) were conducted on the COM dynamics (position, velocity) at time of heel contact and 200 ms after heel contact (Table 11 and Table 12). The warning condition is the explanatory effect of interest (H.1.), with the age group being included as a between-subject effect, as well as second order interaction effects of warning and age group (H.3.).

The ANOVAs conducted on the COM variables evaluated at HC revealed significant differences in the distance of the COM to the left heel in the transverse plane (DCOM) and the anterior posterior COM velocity (VAP COM) between warning conditions (Table 11, Figure 17 a, e). Specifically, subjects walked with a strategy that reduced the frontal plane distance between their COM and left-heel at heel contact, as suggested by the 7.4% decrease in DCOM between the alert and baseline conditions. Both young and older subjects' COM velocity in the anterior-posterior direction was affected differently by the warning condition. The VAP COM increased in the alert dry conditions (4.1%) compared to baseline levels. There was no age significance observed in any of the ANOVAs.

Table 11: Anticipation effects on COM dynamics at HC

Dependent variable	**Independent variable**	**P value**
DCOM	Warning Condition	**<.0001**
	Age	0.1396
	Age*Warning	0.6520
ORCOM	Warning Condition	0.6748
	Age	0.9070
	Age*Warning	0.5314
UP COM	Warning Condition	0.0756
	Age	0.5539
	Age*Warning	0.5875
VML COM	Warning Condition	0.6817
	Age	0.9481
	Age*Warning	0.4915
VAP COM	Warning Condition	**0.0024**
	Age	0.0509
	Age*Warning	0.0617
VUP COM	Warning Condition	0.8421
	Age	0.3492
	Age*Warning	0.3522

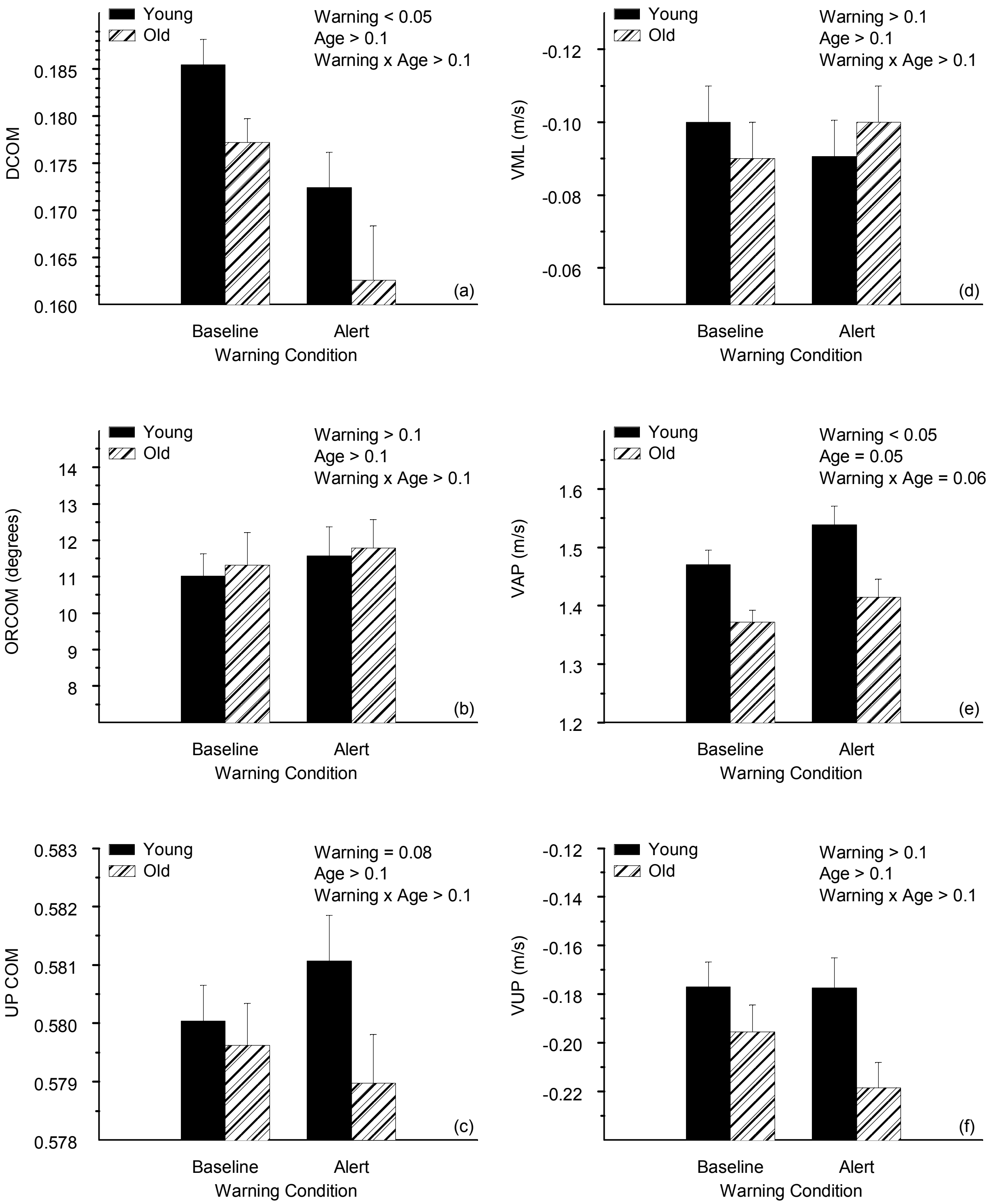

Figure 17: COM variables divided by Age Group at time of HC (Appendix)

The ANOVAs conducted on the COM variables evaluated at 200ms after HC revealed significant differences in the orientation of the COM in the transverse plane (ORCOM), the vertical COM position (UP COM), the anterior posterior COM velocity (VAP COM), and the vertical COM velocity (VUP COM) between warning conditions (Table 12, Figure 18 b, e, f). Specifically, subjects favored a strategy where the COM line of progression, normalized to walking direction, was oriented farther away from the left heel at 200ms after time of heel contact (ORCOM). Specifically, the ORCOM increased 43.7% in alert conditions compared to baseline levels. In addition, the vertical COM (UPCOM) increased 0.3% during the alert dry trials, suggesting that subjects placed the COM farther from the floor. For the VAP COM, subjects walked with a higher anterior-posterior velocity, as evidenced by the 5% increase in the alert dry condition in comparison to baseline trials. Furthermore, subjects walked with a lower vertical velocity, as suggested by the 5.9% decrease in VUP COM in the alert dry condition in comparison with baseline. Finally, it’s worth noting that that age had no significant impact on COM position or velocity.

Table 12: Anticipation effects on COM dynamics at 200ms after HC

Dependent variable	**Independent variable**	**P value**
DCOM	Warning Condition	0.1172
	Age	0.3589
	Age*Warning	0.4973
ORCOM	Warning Condition	**<.0001**
	Age	0.5140
	Age*Warning	0.4654
UP COM	Warning Condition	**<.0001**
	Age	0.1757
	Age*Warning	0.9784
VML COM	Warning Condition	0.4203
	Age	0.8828
	Age*Warning	0.4986
VAP COM	Warning Condition	**0.0004**
	Age	0.0753
	Age*Warning	0.3383
VUP COM	Warning Condition	**0.0004**
	Age	0.3175
	Age*Warning	0.6604

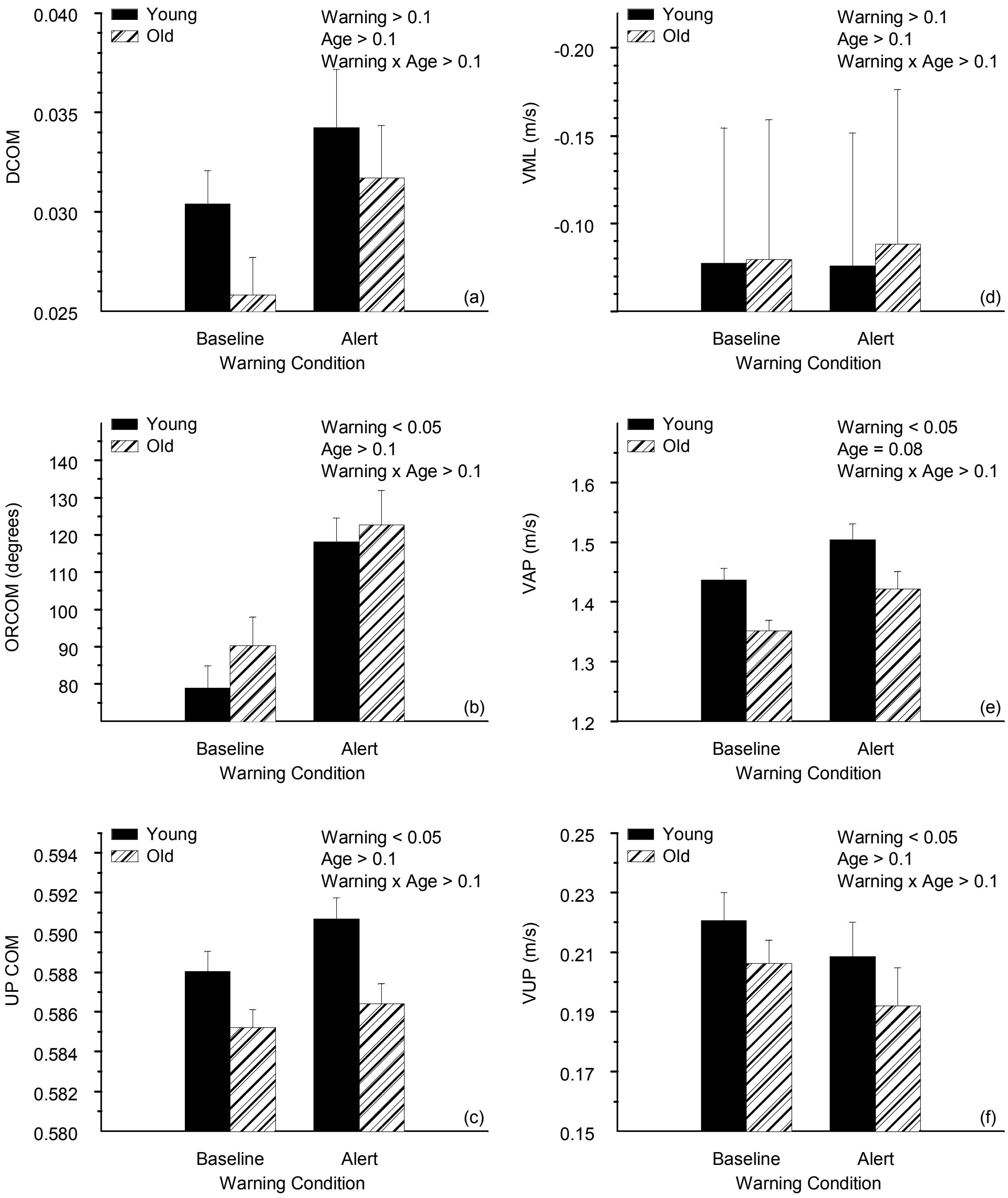

Figure 18: COM variables divided by Age Group at time of 200 ms after HC (Appendix)

In a separate analysis, the testing of H.2 includes the slippery trials collected under the three warning conditions (unexpected, alert and known). Both young and old individuals had similar slip outcomes for the unexpected slip (Table 13).

Table 13: Slip outcome by age, divided by condition (H.2)

	Unexpected Slip		Alert Slip		Known Slip	
	HZ	NH	HZ	NH	HZ	NH
Young	66.7%	33.3%	20.0%	80.0%	6.3%	93.8%
Old	63.6%	36.4%	20.0%	80.0%	0.0%	100.0%

A one-factor within-subject ANOVA was conducted on the recovery time of the COM trajectory (Table 14), both for raw and normalized time data (quantified as explained in the formulation of H.2.), with the independent factor being the warning condition. In addition, the age group was included as an additional (between-subject) effect as well as second order interaction effects of warning and age group.

The ANOVAs on both the normalized and raw (Figure 19) recovery time indicated a significant relationship in Warning Condition only (Table 14). Specifically, the recovery time normalized to stance the alert slip and known slip decreased by 36.1% and 47.1% respectively in comparison to the unexpected slip. For the raw recovery time (expressed in seconds) the recovery time decreased by 38.5% in the alert slip and by 48.4% in the known slip compared to the unexpected slip. Aging effects were not significant (H.3.).

Table 14: Recovery Time with Anticipation

Dependent variable	Independent variable	P value
Normalized Recovery Time	Warning Condition Age Age*Warning	**<.0001** 0.9781 0.7872
Raw Recovery Time	Warning Condition Age Age*Warning	**<.0001** 0.5923 0.8881

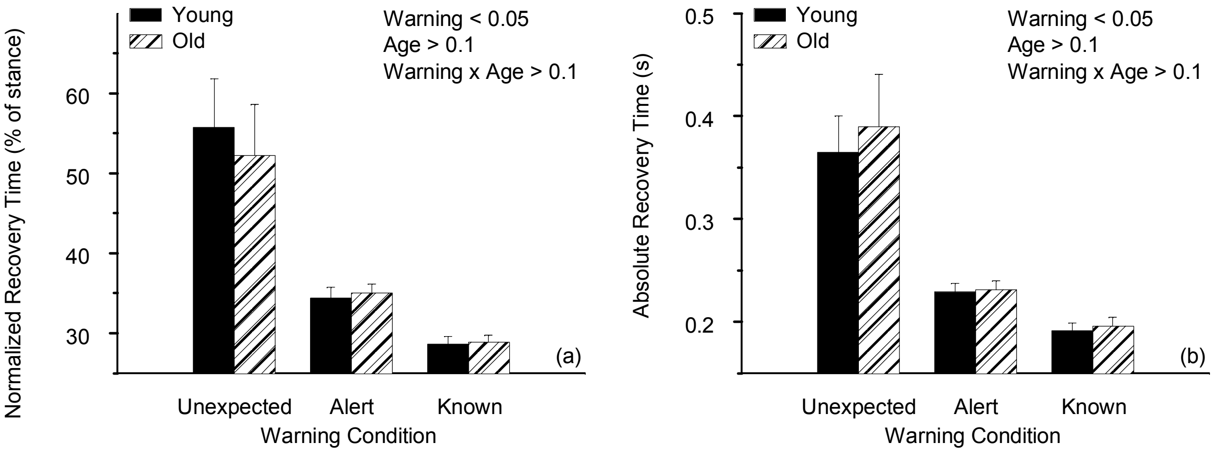

Figure 19: Recovery time, normalized (a) and raw (b) by Age Group

6.0 DISCUSSION

This study investigated the prospect that the COM has an impact on slip dynamics. Two major components were investigated; the impact of the COM dynamics on slip velocity for an unexpected slip (SA1) and the effect of anticipating slippery floors on COM-related postural adjustments, i.e. impact of feedforward adjustments on COM dynamics (SA2). Additionally, the impact of aging on the findings of SA1 and SA2 were investigated in the third hypothesis of each Specific Aim of this research project. The findings presented by this study indicate that there is a significant relationship between several components of the COM kinematics and slip severity, a significant impact of anticipation on the COM, and a no age effects on the COM variables.

6.1 SPECIFIC AIM #1 DISCUSSION

The results pertaining to the unexpected slip illustrate that there are three important COM variables evaluated at HC which impact slipping severity. Specifically, maintaining the COM closer to the leading/slipping leg in the transverse plane at HC (DCOM) reduced slipping velocity. Also, the magnitude of the slipping perturbation was positively correlated with increases in the subject-normalized distance of the COM from the ground (UPCOM) and faster medial-lateral COM velocity (VML COM) evaluated at HC. Thus, in the context of the original hypothesis for SA1, this study favors the rejection of the first two hypotheses in Aim 1.

Previous studies have investigated the impact of COM placement and initial COM velocity on the outcome of a slip using static and dynamic models of the body. Unfortunately, there is limited data for comparison of unexpected slips using true slipping perturbations. Most existing studies using experimental slips have focused on the effects of anticipation and are thus limited in data for comparison. Few studies have attempted to use BOS translation perturbations to simulate slips. However, it is important to note that the heel dynamics at the foot-floor interface in a real slip (little/no shears) differ from the heel dynamics in BOS translations. Regarding studies that have used simulated or modeled slips, there is some disagreement in the results, presumably due to differences in the nature of the modeled perturbation considered in the investigations. For example, while Pai and colleagues originally suggested that a higher DCOM would increase the chances of a small slip perturbation [29], a later study by Pai and colleagues involving a dynamic BOS predicted that to minimize slip magnitude a smaller DCOM and higher VAP COM are desired [30]. The difference between these two studies is that the BOS was static (not moving) versus a dynamic BOS in the latter. The thesis results regarding the impact of the COM position at heel contact (DCOM) agree with the findings of Pai's paper using a moving BOS [30]. However, in an experimental study, anterior posterior COM velocity (VAP COM) was found to play a signification role in slip-recovery biomechanics [23]. In this study it was found that the anterior-posterior COM velocity evaluated at HC was not correlated with slipping velocity. This finding is discussed further in this section.

In H.1, it was hypothesized that a more effective strategy to recover from an unexpected perturbation was to maintain the COM closer to the trailing (non-slipping leg). If the COM is held closer to the trailing leg, a feasible strategy to minimize slip severity was to transfer the weight back to the more stable, trailing (non-slipping) leg. However, the results now indicate that the more effective strategy is to maintain the COM closer to the foot that the body weight is being transferred to, even if it's during a slipping perturbation. Subjects who employed this strategy experienced a less severe slip. This is illustrated in the lower distance of the COM to the left heel in the transverse plane (DCOM), increasing the normal force exerted through the leading foot, thereby reducing slipping tendency through less available friction. Furthermore, a lower vertical position (UP COM) facilitates smaller energy expenditure to move the COM in the vertical direction, allowing greater control. Finally, a low medial lateral velocity (VML COM) indicates that the movement of the COM from side to side is reduced at HC, once again maintaining the COM in a region of increased influence, or 'base of support'. There may be an optimal placement of the COM within this base of support; however it is beyond the confines of this report.

Similarly, the formulation of H.2 was supported by previous studies [30]. However, in the thesis results it was found that the anterior-posterior COM velocity evaluated at HC was not correlated with slipping velocity. This discrepancy could be due to the relatively tight VAP COM variability in this study, i.e. subjects walked with a similar gait velocity (overall mean of 1.45 ± 0.13 m/s) due to the restriction in the laboratory walkway setup.

Regarding the effects of age (H.3), there no significant difference of COM position or velocity between young and older adults. Once again, research of age effects on unexpected slips is limited, but previous studies found that older adults fell more than their younger counterparts [23]. In this study, the fraction of hazardous/non-hazardous outcomes is similar between young and older adults (Table 6). This lack of significance could be due to the limited sample size, the relative 'youth' of the older population sampled, or the relative physical fitness of the older adults in comparison to the entire population. A larger study involving a greater older population with a wider variation in ages would fully identify any relevant age significance present.

The implications of this research are two-fold. First, using the COM, individuals who fall outside this region of stability can be identified as ‘prone to slip’. Secondly, people can be trained to walk differently in order to minimize the occurrence or magnitude of a slip. However, further research must be performed in order to quantify the impact such a shift in walking pattern would have on the daily life of an older individual (e.g. energy expenditure, other gait perturbations, stiffening strategies).

6.2 SPECIFIC AIM #2 DISCUSSION

The results pertaining to anticipated slips indicated that there are two COM variables evaluated at HC and four COM variables evaluated at 200ms after HC which effect slip severity. Specifically, at time of HC, subjects significantly altered their COM location in the transverse plane to maintain the COM closer to the leading/slipping leg (DCOM). In addition, the anterior posterior velocity (VAP COM) was positively correlated with anticipation effects. In comparison, at 200ms after HC, subjects significantly altered their COM to maintain the COM closer to the body centerline (ORCOM). Also, anticipation effects were associated with a raised overall body position (UP COM), a reduced vertical velocity (VML COM) and increased anterior posterior velocity (VAP COM). Furthermore, a reduction in recovery time, where the COM was brought over the left heel, was observed with anticipation conditions. However in both COM variables at HC and 200ms after HC there were no significance in regards to age. Thus, in the context of the original hypothesis for SA2, this study supports the acceptance of hypotheses H.1 and H.2 associated with Specific Aim #2.

Previous studies have examined the impact of anticipation on COM placement and velocity using experimental slips under a known anticipation condition. For example, both studies by Marigold and Patla and You and colleagues suggested that a lower DCOM coupled with a higher VAP COM at time of HC is a common strategy in response to anticipation effects [26,28]. A further analysis by You and colleagues indicated that in order to recover from a slipping perturbation, the COM must be brought over the perturbed foot (Recovery Time) as well as increase in anterior posterior velocity (VAP COM) [28]. The results regarding the impact of the COM position and velocity at both HC and 200ms after HC agreed with these previous studies, in that a lower DCOM at HC, a higher overall VAP COM, and a reduction in recovery time of the COM were seen with anticipation conditions.

Originally during the formulation of H.1 and H.2, it was postulated that a more effective strategy is one of 'getting over' the slip. The goal of corrective reactions generated in response to a slip is to bring the center of mass over the base of support as fast as possible. This is illustrated at time of HC by strategic COM placement. The COM is placed closer to the slipping foot (DCOM) thereby creating less work for the body to shift the COM forward while increasing the anterior posterior velocity (VAP COM). After the slip has occurred (at 200ms after HC) the subject maximizes control over the COM by strategic placement and advancement. The COM is held closer to the centerline of the body (ORCOM) in order to maintain greater control and stability and the anterior posterior velocity (VAP COM) remains higher in comparison to baseline trials. These combine to propel the COM past the slip and onto the next stage of the gait cycle. In summary, an effective strategy leading up to a slip is a combination of moving the

COM closer to the body and increasing anterior posterior COM velocity. After HC has occurred, an individual raises their overall body position as well as reducing their vertical velocity to regain control. This leads to an increased recovery time for a potential slip occurrence.

Regarding the effects of age (H.3), like the results for Specific Aim #1, there were no COM variables significant with age for anticipation conditions. While previous studies found that older adults fell more than their younger counterparts [23] the alert and known slips showed no such differences in slip outcome (Table 13). It appears that for anticipation effects, there were no evident distinctions between young and older adults and their COM placement.

The implications of this anticipation results have a significant impact on future research. A clear difference is present in the placement and velocity of COM variables during warning conditions. These are measurable differences that sum the entire body's response to a potential slipping perturbation. Future work can now focus on identifying what postural parameters cause this shift in the COM and targeting these parameters in further analysis.

6.3 LIMITATIONS

Two limiting factors to the thesis work are of note. The first is restrictions imposed by the subject protocol on gait speed. The walkway setup used in testing in conjunction with the subject instructions to walk at a self chosen speed resulted in a relatively consistent gait speed across subjects (Table 7). This limited variability in gait speed resulted in its independence from slip severity (Table 5). However, it is known that people walk with varying gait speeds, especially during inclement weather and potential hazardous footing (Table 11, Figure 17 e). Future work focusing on COM variables and slip severity should incorporate variations in gait speed (walk fast, walk slow, walk normal, etc.) in order to fully elucidate the impact of a slip condition. The second limiting factor lies within the anthropometric data by Chandler [31]. Anthropometric data regarding center of mass is limited. An extensive literature review was performed to gather all available segmental center of mass descriptions. The Chandler data set used in this research involved five male cadaver subjects. The data neglects both gender and age differences in the human body. Due to the fact that both older and female subjects have a different weight distribution in comparison to their young male counterparts, this is a restriction in the interpretation and practical significance of this thesis work. If more comprehensive data pertaining to female and older anthropometry can be found, the kinematic data can be reprocessed to incorporate these new findings.

6.4 CONCLUSION

In summary, there are two strategies at present during slips (1) to maintain control over the COM and (2) to get over the slip as quickly as possible and continue the gait cycle. The significance of this research indicates that tracking COM dynamics may be helpful in differentiating between postural strategies that successfully recover balance and responses that result in falls. In addition, quantifying the effects of anticipation provides a baseline for identification of postural responses and their potential modifications that may significantly impact slip severity.

APPENDIX

ABBREVIATIONS

Abbreviation	**Definition**
STF	Slips, trips, and fall
COM	Center of Mass
RCOF	Required Coefficient of Friction
BOS	Base of Support
PSV	Peak Slipping Velocity
HC	Heel Contact
TO	Toe Off
EOS	End of Slip
TSD	Total Slip Distance
ML COM	Mediolateral Center of Mass
AP COM	Anterior-Posterior Center of Mass
UP COM	Vertical Center of Mass – normalized to body height
VML COM	Velocity of the Mediolateral Center of Mass
VAP COM	Velocity of the Anterior Posterior Center of Mass
VUP COM	Velocity of the Vertical Center of Mass
DCOM	Distance of the Center of Mass relative to the left heel – normalized to body height
ORCOM	Orientation of the Center of Mass relative to the left heel
GS	Gait Speed
SW	Step Width
SL	Step Length

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