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**Effects of Musculoskeletal and Sensory Degradation due to Aging
on the Biomechanics of Slips and Falls**

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Abstract

The proposal called for a one-year study to investigate the process of initiation and recovery of inadvertent slips and falls. The specific aim of the proposed research was to investigate the changes in the biomechanical parameters of walking and ground reaction forces due to intrinsic deficits associated with increase in age. More specifically, how deterioration of muscular strength and sensory degradation among older individuals affect biomechanical parameters of slip and fall accidents under normal and abnormal conditions.

The investigation compared biomechanical parameters of walking in three age groups; (18-30 years), (35-59 years), and 65 years or over). Biomechanical parameters included; stride length, heel velocity, required coefficient of friction, slip distance, and position and velocity of center of gravity of the whole body during heel contact phase of the gait. These parameters were measured utilizing force platforms, a 3-D motion analysis system, and a fall arresting rig. To determine the position and velocity of center of gravity during heel contact phase of the gait, a 3-D link (14) segment model was utilized. Walking surfaces included oily vinyl tiles (dynamic coefficient of friction (DCOF) = 0.08) and outdoor carpet (DCOF = 1.80). Subjects walked according to their natural cadences. A sensory organization test was also performed to obtain information concerning the subject's proprioceptive, visual and vestibular systems. These sensory components were measured using an Equitest Posturography Platform. In addition, isometric strength test was performed (using a force transducer) to obtain information concerning the subject's over-all strength.

The results indicated that younger subjects slipped as often as the elderly subjects, however, the recovery process of older individuals was much slower and less effective. The ability to successfully recover from a slip (thus preventing a fall) is believed to be affected by lower extremity muscle strength and sensory degradation in elderly individuals.

Significant Findings

This section summarizes the principal experimental findings and discusses them with respect to the experimental hypotheses presented in the proposal.

Initiation of Slips

Older age group's RCOF will be higher than younger counterparts due to the muscle weakness and initial gait characteristics.

As indicated by many researchers, initial gait characteristics such as step length and heel velocity may affect RCOF due to the increase in horizontal foot force. Consistent with previous findings, the step length of older individuals was shorter than their younger counterparts and the heel velocity of older individuals was on the average faster than that of younger individuals. However, the results from this investigation indicated that older age group's required coefficient of friction (RCOF) was not significantly higher than their younger counterparts (although overall mean of the RCOF was higher for the older individuals). These results are somewhat confounding due to the fact that shorter step length of the older individuals should have resulted in lower overall mean value of RCOF. This generalization leads us to believe that the higher heel velocity may have affected RCOF, however, when we look carefully how RCOF is calculated (at peak 3), the instantaneous heel velocity at heel contact may have minimum effect on the RCOF (due to the heel already being on the ground and going backwards at this instance.) Furthermore, bivariate correlation analysis between RCOF and heel velocity (HV) have indicated no statistically significant relationship ($R = .1177$, $p = .286$). These findings suggest that there might be other variable(s) affecting RCOF. Bivariate correlation analysis between RCOF and center of gravity velocity before heel strike (COGVB) and center of gravity velocity after heel strike (COGVA) indicated statistically significant relationship ($R_{\text{COGVB}} = .29$, $p_{\text{COGVB}} = .007$; $R_{\text{COGVA}} = .46$, $p_{\text{COGVA}} = .0001$). These results suggest that the RCOF is affected by walking velocity (or COG velocity) rather than heel velocity of the subjects. Furthermore, $\text{COGB}_{\text{diff}}$ may have greater influence on RCOF values than the all other variables discussed so far. As indicated in the results, younger individuals were able to transfer their COG faster than older

individuals on the carpeted surface, this faster transfer of COG may have decreased the ratio of horizontal to vertical force (i.e., RCOF) for the younger individuals.

In conclusion, older age group's RCOF was not significantly higher than their younger counterparts, and initial gait characteristic such as heel velocity did not significantly influence RCOF. In addition, based on the analysis of slip distances (particularly the SDI1), younger individuals as well as the older individuals were susceptible to slips. These results indicate that initiation of slips are far more complicated than thought before, and younger individuals as well as older individuals are susceptible to slips.

Detection and Recovery

Older age group's slip performance measures (e.g., slip distance, sliding heel velocity, heel acceleration and adjusted required coefficient of friction) will be poorer (less optimally adjusted to maintain balance) than younger counterparts. This will be seen clearly in the evaluation of slip performance measures.

Older age group's slip distances will be longer than younger counterparts due to the muscle weaknesses and sensory degradation. This will be seen clearly in the evaluation of relationship between sensory degradation and muscle weakness to slip distances.

Irrespective of the activity being performed or the environmental factors associated with the occurrence of a potential fall, there are certain processing stages that the central nervous system must undertake (detection phase) if a fall is to be avoided or compensated for (recovery phase). First, during the detection phase, if a potential slip and fall is imminent, sensory input must trigger or alert those centers responsible for response selection. This alerting process may be initiated by one or more of the following sensory inputs; proprioception, vision, and /or vestibular function. The result of the Sensory Organization Test indicated that equilibrium scores were lower for older individuals due to sensory degradation (especially vestibular). In addition, muscle latency time (reaction time) was longer for older individuals as compared to their younger counterparts. The effect of the sensory degradation is further supported by higher adjusted required coefficient of friction (ARCOF). On the average, the ARCOF of the younger individuals (.074) was adjusted within the dynamic friction requirements (.08). However, on the

average, middle (ARCOF - .10) and older individuals (ARCOF - .12) could not adequately adjust their ARCOF values. Consequently, the result was longer slip distance and higher frequency of falls. The prediction model further supports that the vision, reaction time and muscle strength (lower extremity) were important for determining slip and fall severity.

In conclusion, all subjects (young and old) slipped under slippery conditions. However, the older individuals could not control their slips, which led to more falls. Inability to control slipping responses may be a result of sensory degradation and muscle weakness. Most of the current research on slips and falls concentrates predominantly on initiation of slips (i.e., RCOF), however, this study indicates that recovery, or attempted recovery in a fall is important as well. Therefore, future research should focus not only on the dynamics of slips, but also the dynamics of falls.

Work Demand

Increasing the work demand (induced by the load) will affect the gait of older groups more than their younger counterparts in ways that make slip and fall accidents more likely.

Although only a light load was used in this study, the load effect was much more pronounced for the older individuals than their younger counterparts. In terms of initiation of slip, the overall average RCOF (age x load) indicated that the RCOF of older individuals was higher for the load condition than the no-load condition. In addition, vertical COGVA was significantly faster for the load condition than the no-load condition. Thus, the additional jarring effect and increased slip tendency (e.g., higher horizontal force) due to the load carriage increased the older individuals risk for initiation of slips and falls. In terms of detection and recovery of slips and falls, the slip distance of older individuals was affected by a load more than their younger counterparts. On the average, the slip distance of older individuals was longer for the load condition than the no-load condition. Thus the added task of load carriage may increase the likelihood of slip and fall accidents of older individuals more than their younger counterparts.

Usefulness of Findings

This research project was undertaken to quantify gait parameter differences between older and younger individuals under inadvertent slip and fall situations. previous studies of slip and fall accidents have focused largely on young individuals and have not addressed the effects of age-related physiological deficits on biomechanics of slips and falls. In this project, intrinsic changes associated with aging such as the gait adaptation, musculoskeletal and sensory degradation and its effect on the initiation, detection, and recovery processes was evaluated to answer the question of why older adults are exposed to a higher likelihood of slip-induced falls. The findings suggest that both muscle strength and sensory abilities play an important role in preventing slip and fall accidents. Additionally, gait changes associated with aging played an important role in initiation and recovery of slips and falls.

Publications

The following publications resulted from the grant:

- Lockhart, Thurmon E., Smith, James L., Woldstad, Jeffrey C., and Li, Pingsham, "Effects of Musculoskeletal and Sensory Degradation Due to Aging on the Biomechanics of Slips and Falls", Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA. pp. 5-83 – 5-86.
- Lockhart, Thurmon E., Woldstad, Jeffrey C., Smith, James L., Hsiang, Simon, and Li, Pingsham, "Prediction of Falls Using a Robust Definition of Slip Distance and Adjusted Required Coefficient of Friction", Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA. pp. 4-506 – 4-509.
- Lockhart, Thurmon E., Smith, James L., Woldstad, Jeffrey C., and Hsiang, Simon, "Age Effects of Horizontal Heel Contact Velocity and Initiation of Slips and Falls", 2000, submitted to *Human Factors*.

EFFECTS OF MUSCULOSKELETAL AND SENSORY DEGRADATION DUE TO AGING ON THE BIOMECHANICS OF SLIPS AND FALLS

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A laboratory study was conducted to examine the initiation and recovery from foot slips among different age groups utilizing biomechanical parameters, muscle strength, and sensory measurements. Forty two subjects from three age groups (young, middle, and elderly) walked around a circular track at a comfortable pace, while carrying a light load and while unloaded. Slippery floor surfaces were placed on the track over force platforms at random intervals. The results indicated that younger subjects slipped as often as elderly subjects, however, the recovery process of older individuals was much slower and less effective. The ability to successfully recover from a slip (thus preventing a fall) is believed to be affected by lower extremity muscle strength and sensory degradation of the elderly individuals.

INTRODUCTION

Injuries associated with slip and fall accidents continue to pose a significant problem to industry, both in terms of human suffering and economic losses. Fall accidents are the second leading cause of work-related fatalities next to motor vehicle accidents and, the number of fatal falls exceeds the combined number of workplace deaths associated with electric current, fire, poison, burning, and drowning (National Safety Council, 1993; Leamon and Murphy 1995). Many studies have shown that with advancing age there is an increasing incidence of fatal slip and fall injuries (Agnew and Suruda, 1993; Rubenstein et al., 1988; and Campbell et al., 1981). Falls are the leading cause of death resulting from injury among older people (over age 75), and the second highest cause of accidental death for 45-75 year olds (National Safety Council, 1998). The National Safety Council reported that in 1997, 14,900 Americans met their death by falling, and of these deaths, 12,000 were people over 65 years of age (National Safety Council, 1998).

Although much has been learned over the last few decades about the deterioration of muscular strength, gait adaptations (i.e. higher heel velocity [Winter et al., 1990]) and sensory degradation among older individuals, still little is known about how these intrinsic changes affect biomechanical parameters associated with slip and fall accidents.

The objective of this research was to investigate the process of initiation and recovery of inadvertent slips and falls. It was hypothesized that deterioration of lower extremity muscular strength, higher heel velocity at heel contact, and sensory degradation among older individuals would affect the severity of slips (as measured by gait parameters such as the heel velocity, slip distance, slipping heel velocity, etc.) more than their younger counterparts. This research will provide a better understanding of the gait characteristics of different age groups as they walk on slippery floor surfaces, and allow engineers to design better work environments to reduce the incidence of slips and falls among older workers.

METHOD

Subjects. Fourteen young individuals (7 male and 7 female), 14 middle-aged individuals (7 male and 7 female), and 14 older individuals (7 male and 7 female) participated in this experiment. Subject's age, height and weight information is presented in Table 1.

Table 1. Subject information

	Young (18-29 yrs.) Mean (S.D.)	Middle (35-59 yrs.) Mean (S.D.)	Old (65 yrs. and over) Mean (S.D.)
Age (yr)	22.6 (2.1)	46.9 (13.6)	75.55 (6.76)
Ht (cm)	169.7 (6.1)	173.5 (6.3)	170.2 (6.4)
Wt (kg)	68.7 (9.6)	75.5 (16.1)	76.8 (13.3)

The young subjects were recruited from the general student population at Texas Tech University and older subjects were recruited from the local community. All participants were compensated for their time and effort.

Apparatus. Two commonly used floor materials were used in this experiment: outdoor carpet (Beau Lieu ¼" Olefin) and vinyl tile (Armstrong). The vinyl tile surface was covered with motor oil (10W40) to reduce the coefficient of friction (COF). The available dynamic COF (ADCOF) for each surface was measured using a standard 4.54 Kg (10 lb.) horizontal pull slipmeter with a rubber sole material and found to be 1.80 for the outdoor carpet and 0.08 for the oily vinyl tile. Walking trials were conducted on a circular track (20 meter in circumference) using an overhead fall arresting rig as shown in Figure 1. The wooden deck was approximately 6.7 meters x 6.7 meters. The entire deck was covered with carpet. A remote controlled floor changer (RCFC) was used to change the test floor surfaces so as to provide unexpected slippery conditions. The RCFC unit was composed of a DC motor (LEESON Electric Corp.) and a gliding shaft (ACME Thread) attached to a platform. The DC motor was controlled by a remote control unit. Once triggered, the DC motor turned the

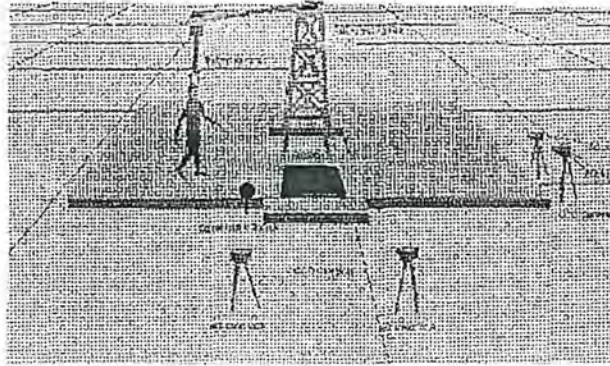


Figure 1. Field layout of the experiment.

ACME thread (max. 1750 rpm) thereby, moving the platform to a desired floor level. The test surfaces were mounted on a platform, which was connected to the force plates. The overall function of the system allowed a subject to walk under experiment conditions without being aware of the floor surface change. A fall arresting rig was used to protect subjects from falling during the experiment. The rig consists of a full-body parachute harness attached to an automated overhead suspension arm. A feedback control system allowed the arm to sense the position of the subject and increase or reduce velocity to stay overhead. The rig was designed to permit the subject to fall approximately 15 cm before arresting the fall and stopping the forward motion. An Ariel Performance Analysis System (APAS) and four Panasonic video recorders (CCD) were used to collect the three-dimensional posture data of the subjects as they walked over the test surface. Posture data were sampled and recorded at a rate of 60 Hz. The ground reaction forces of the subjects walking over the test surfaces were measured using two Bertec force plates also sampled at a rate of 60 Hz. A Sensory Organization Test (balance assessment) was performed utilizing the NeuroTest System (NeuroCom Inc.). A wooden container (46 cm x 30 cm x 30 cm, 3 kg) was used for the carrying task.

Procedure. The subjects were scheduled to participate in two testing sessions within one week's time. The subjects attended a familiarization session before the experiment. During the familiarization, the fall arresting system and walking conditions were introduced. Whole-body isometric strength measurements for the arms, legs, and torso was collected as described by Chaffin et al. (1978) and Chaffin and Andersson (1991). Afterwards, the NeuroCom Sensory Organization Test was performed to measure sensory function and balance. During the experiment, the subjects walked across each floor condition for 10 min with and without the load (total of 20 minutes). While walking, subjects were instructed to focus their eyes on a light emitting diode located approximately 2 meters above and 3 meters away from the testing area. A secondary task that required them to call out when the light was on and when it was off was used to ensure that they attended to the LED. During each of the 10 min sessions, 2 slippery conditions were randomly introduced by the system, and measurements

of subject's posture and ground reaction forces were recorded. Location of the slippery surfaces were also randomly distributed by the two floor changers (e.g. two force plate locations). Standard shoes with rubber soles were supplied to all subjects to maintain a constant COF level. Subjects were also supplied with a walkman (listening to old comedy routines) during the walking experiment to conceal any sound of the floor changer's motors.

Treatment of Data. The converted coordinate data for each of the 26 body markers (defining a 14-segment whole body model [MacKinnon and Winter, 1993]) and the ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (Winter, 1990). Residual analyses of the difference between the filtered and unfiltered signals over three different cutoff frequencies (6, 10, and 12 Hz) determined 6 Hz as the preferred cutoff frequency. The dependent measures, heel velocity (HV), and step length index (SLI) were analyzed using a $3 \times 2 \times 2$ (age x floor x load) three-way repeated measures analyses of variance (ANOVA); RCOF, adjusted RCOF (ARCOF), slip distance (SD) and, sliding heel velocity (SHV) were analyzed using a 3×2 (age x load) two-way repeated measures analyses of variance with $\alpha = 0.05$. For these analyses floor and load were treated as within-subjects effects, while age was a between-subjects effect. In addition, Sensory Organization Test scores and Muscle Control Test scores were analyzed using a one-way repeated measures ANOVA with age groups as the independent variable ($\alpha = 0.05$).

The p-values in the ANOVA were adjusted for violations of the assumptions regarding the variance-covariance matrix using the Huynh-Feldt method to estimate ϵ and adjusting the degree-of-freedom accordingly (Winer et al., 1991). In addition, constant variance and normality assumptions were verified using residual analysis and normality plots. A computer algorithm was written in the C++ 6.0 to objectively determine the dependent measures.

Calculations of dependent measures: The step length index (SLI) was calculated from the difference between right and left positions of the heel markers during the heel contact phase of the gait cycle divided by subject's height. Heel contact was defined as the time when the vertical ground reaction force (GRF) exceeded 10N (to synchronize kinetic and kinematic variables, a LED was coupled to the vertical force output of the force platform, when the force exceeded 10N, a LED was triggered).

The instantaneous heel velocity (HV) at heel contact was calculated utilizing the heel velocities in horizontal direction at the foot displacement of 1/60 second before and after the heel contact phase of the gait cycle.

The required coefficient of friction (RCOF) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force after heel contact (peak 3 as defined by Perkins and Wilson, 1983) on the carpeted floor surface.

Adjusted RCOF (ARCOF) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force at the end of the slip-stop point on the oily vinyl tile surface.

Slip distance (SD) (the horizontal distance traveled by the foot after the heel contact phase of the gait cycle) was

measured utilizing heel coordinates between slip-start and slip-stop points on the vinyl floor surfaces. The slip-start point was defined as a point where non-rearward positive acceleration of the foot after heel contact occurred and, slip-stop point was defined as a point where maximum heel velocity (end of positive acceleration) of the heel occurred after slip-start point.

The relative sliding velocity (SHV) of the heel after heel contact was measured by averaging the velocity of the heel during slipping (period of SD).

The Sensory Organization Test (SOT) (balance test) scores were calculated by comparing the angular difference between the subject's calculated maximum anterior to posterior COG displacements to theoretical maximum displacement which was expressed as a percentage between 0 and 100, with 0 indicating sway exceeding the limits of stability and 100 indicating perfect stability.

The Muscle Control Test (MCT) scores were calculated by measuring muscle latency response in milliseconds between the onset of a translation and the onset of the subject's active response to the support surface movement.

The lower leg strength index (LLI) was calculated by dividing the subject's body weight from the isometric lower leg strength measurements.

RESULTS

To conserve space, only effects related to the age variable will be presented. The ANOVA analysis of SLI showed significant effects for age groups ($F(2,39) = 6.676, p=0.003, \epsilon = 1.053$). In general, older subjects SLI were shorter than younger subjects, and middle age subjects had longest SLI on the average. Table 2 summarizes the mean values and standard deviations for each of the dependent measures as a function of age.

On the average, the older individuals mean HV was faster than the younger individuals HV, however, the ANOVA analysis of HV indicated no statistically significant difference between three age groups ($F(2,39) = 4.817, p=0.067, \epsilon = 1.053$).

Although the means of the RCOF was higher for the older individuals than younger counterparts, the ANOVA analysis of RCOF indicated no statistically significant difference ($\alpha = 0.05$) between three age groups ($F(2,39) = 2.392, p=0.105, \epsilon = 1.053$).

Table 2. Summary of Gait Parameters.

Variables	Young Mean (S.D.)	Middle Mean (S.D.)	Elderly Mean (S.D.)
Step L (m)	64.35 (7.34)	67.63 (9.05)	59.12 (7.67)
SL Index	.381 (.04)	.393 (.04)	.347 (.03)
Hor. HV (cm/s)	31.03 (21.5)	32.11 (13.5)	42.37 (26.7)
RCOF (carpet)	.176 (.01)	.188 (.02)	.192 (.02)
ARCOF (vinyl)	.074 (.01)	.10 (.01)	.12 (.01)
SD (cm)	4.98 (4.8)	7.65 (4.9)	11.80 (9.4)
SHV (cm/s)	44.05 (35.1)	63.95 (31.7)	74.14 (39.7)
SOT (%)	83.85 (3.75)	77.6 (3.65)	68.13 (7.2)
MCT (ms)	123.7 (10.8)	131.4 (7.5)	139.7 (5.2)

Lockhart (1977) reported that elderly individuals could not reduce the adjusted RCOF (ARCOF) to available dynamic COF as well as younger subjects on slippery floor surfaces (oily vinyl tile). ARCOF is the measured ratio of the horizontal foot force to the vertical foot force at the slip-stop point and represents the subjects ability to adjust dynamic friction requirements to recover from further slipping. Consistent with previous findings, older individuals ARCOF was significantly higher than younger counterparts ($F(2,39) = 13.434, p=0.0001, \epsilon = 1.053$).

Older individuals SD was significantly longer than the younger counterparts ($F(2,39) = 9.115, p<0.001, \epsilon = 1.053$).

Older individuals SHV was significantly faster than younger individuals ($F(2,39) = 5.536, p<0.007, \epsilon = 1.053$).

The older subjects SOT scores were significantly lower than their younger counterparts ($F(2,39) = 33.27, p<0.0001, \epsilon = 1.053$).

The older subjects MCT time was significantly longer than their younger counterparts ($F(2,39) = 13.77, p<0.0001, \epsilon = 1.053$).

In addition, multiple regression analysis was performed to describe and predict the relationship between the independent variables (age, height, weight, SOT, vision, proprioceptive, vestibular responses, MCT, and strength variables) and the dependent variables (SD). The data were analyzed by utilizing techniques available for evaluating probabilistic process, functional specification of mean response, constant variance, and normality assumptions. The predictor variables were selected by utilizing cp and backward elimination procedure for dependent variable SD. The final model of SD is listed below:

$$SD = -15.785 - .037 (\text{vision}) + .204 (\text{MCT}) - .308 (\text{LLI}).$$

$$(R^2 = .413; F(3,38) = 8.19, p < 0.0003).$$

DISCUSSION

This research project was undertaken to provide a better understanding of how deterioration of muscular strength, gait adaptation, and sensory degradation among older individuals affect the process of initiation and recovery of inadvertent slips and falls utilizing biomechanical parameters of walking.

Initiation

As indicated by many researchers, initial gait characteristics such as step length and heel velocity may affect RCOF due to the increase in horizontal foot force. In general, older individuals step length was significantly shorter than younger counterparts, however, we found no significant difference in HV or RCOF between the three age groups. This result suggests that at the time of initiation of the slips, younger as well as the older individuals are prone to slips. This result is further supported by the classification of slips (Figure 2). Trials were classified as falls if the subject's sliding heel velocity exceeded the velocity of COG (although classified as the fall, it is actually, a slip and fall). In general, younger individuals experienced as many slips as the middle aged, and the elderly.

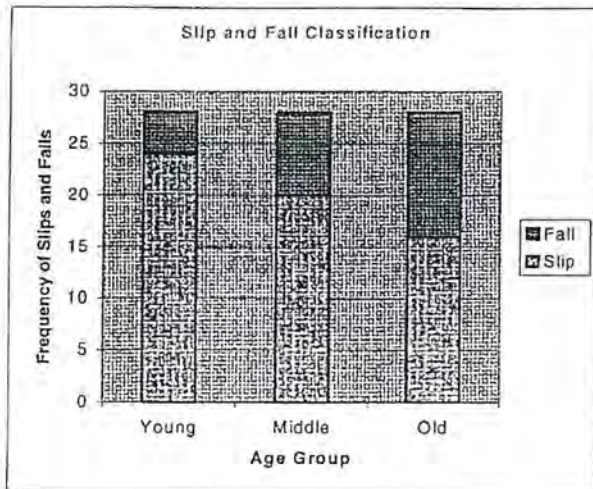


Figure 2. Slip and fall classification by the age group.

Detection and Recovery

Irrespective of the activity being performed or the environmental factors associated with the time of a potential fall, there are certain processing stages that the central nervous system must undertake (detection phase) if a fall is to be avoided or compensated for (recovery phase). First, during the detection phase, if a potential slip and fall is imminent, sensory input must trigger or alert those centers responsible for response selection. This alerting process may be initiated by one or more of the following sensory inputs; proprioception, vision, and vestibular function. The result of the Sensory Organization Test indicated that equilibrium scores were lower for older individuals due to the sensory degradation (especially the vestibular). In addition, muscle latency time (reaction time) was longer for older individuals than the younger counterparts. The effect of the sensory degradation is further supported by higher ARCOF. On the average, the younger individuals ARCOF (.074) was adjusted within the dynamic friction requirements (.08). However, on the average, middle (ARCOF - .10) and older individuals (ARCOF - .12) could not. Consequently, the result was longer slip distance and higher frequency of falls. The prediction model further supports that the vision, reaction time and muscle strength (lower extremity) were important for determining slip and fall severity.

In conclusion, all subjects (young and old) under slippery conditions slipped. However, the older individuals could not control their slips leading to more falls. Inability to control slipping responses may be a result of the sensory degradation and muscle weakness. Most of the current

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PREDICTION OF FALLS USING A ROBUST DEFINITION OF SLIP DISTANCE AND ADJUSTED REQUIRED COEFFICIENT OF FRICTION

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This paper proposes a new method to identify slip distance and adjusted required coefficient friction to predict falls among different age groups. These methods were based on the fact that the dynamics of slips are altered due to the fall arresting rig (or harness) during the critical moment of slips and falls.

INTRODUCTION

Reducing slip and fall accidents has been a topic of interest to many researchers since the 1920s. Traditionally, these researchers utilized four basic approaches to investigate slip and fall accidents; epidemiology, biomechanics, tribology and psychophysics. However, in spite of the improvements in tribometric techniques to assess shoe/floor interactions, and increased knowledge of the biomechanical responses to walking on slippery surfaces, fall accidents continue to represent a significant burden to society, both in terms of human suffering and economic losses. Furthermore, with the general increased life expectancy and increased proportion of the aged workforce as the major segment of overall population (45 to 65 year olds – WHO, 1993), the workplace is likely to experience a greater risk for slip and fall accidents and may have an additional impact on the economics of the health care system and the industries.

A review of literature on slip and fall accidents indicates that multiple mechanisms are involved in slip and fall accidents. In general, fall accidents on level walking surfaces are believed to be the result of a loss of traction between the shoe and the contact surface. The term "slip" has often been used to describe this loss of traction, both when the slip results in a fall and when it does not (Miller, 1983). Recently, slip classifications have been used as a measure of floor surface slipperiness (i.e. severity of slips). In addition to interest in slips and microslips as potential indicators of slipperiness, gait parameters (such as RCOF) at the point of initial foot contact are of interest for tribological studies (Perkins, 1978; Perkins and Wilson, 1983).

In terms of biomechanical approach to prevention of slips and falls, main attention has been focused on studying of slip behavior of the young individuals. Slip behavior has been investigated by many researchers (Perkins, 1978; Strandberg and Lanshammar, 1985; and Leamon and Son, 1989). Actual slip experiments were conducted on subjects wearing test shoes, walking from non-slippery surfaces onto slippery surfaces utilizing a fall arresting rig (and harness) to prevent injuries. In the majority of experiments, slips occurred in a forward direction having started shortly after the heel contacted the contaminated surface. In some cases the shoe only slipped a few centimeters and then stopped, so that the subjects were able to regain balance and continue

walking. In other cases, the foot continued slipping, and the subjects were unable to recover balance. The severity of a slip (whether the slip resulted in a fall) therefore, appears to be dependent on the distance through which subjects slipped (for example, any slip more than 10 to 15 cm in length resulted in loss of balance). Perkins (1978) noted that this effect (slip) is probably related to the acceleration of the foot as it slips forward. He further noted that if the foot travels faster than the body, the body can never catch up, but if the body is able to overtake the slipping foot (whole-body-center-of-gravity speed is greater than the slipping speed of the foot), the frictional force will be increased and therefore, the slip will come to a halt.

Although the above concepts are sound and logical, currently, there exist no universal definitions (nor the robust technique) for assessing slip severity for different age groups (i.e. slip distance, foot acceleration, etc). The purpose of this study was to develop a method to assess slip severity among different age groups. This was accomplished by closely examining the slip behaviors of individuals from three different age groups (young, middle, and elderly), and defining the repeatable gait patterns during the event of slips and falls. It was also to investigate the process of initiation and recovery of inadvertent slips and falls among different age groups utilizing new technique for assessing slip severity (for more detailed description of this result, please see Human Factors Proceeding titled: *Effects of Musculoskeletal and Sensory Degradation due to Aging on the Biomechanics of Slips and Falls*). In this report, the former will be explained in more detail. It was hypothesized that slip severity will be different among three age groups due to the intrinsic changes (i.e. muscle weakness, sensory degradation, etc) associated with aging.

METHOD

Subjects. Fourteen young individuals (7 male and 7 female), 14 middle-aged individuals (7 male and 7 female), and 14 older individuals (7 male and 7 female) participated in this experiment. Subject's age, height and weight information is presented in Table 1.

Table 1. Subject information

	Young (18-29 yrs.) Mean (S.D.)	Middle (35-59 yrs.) Mean (S.D.)	Old (65 yrs. and over) Mean (S.D.)
Age (yr)	22.6 (2.1)	46.9 (13.6)	75.55 (6.76)
Ht (cm)	169.7 (6.1)	173.5 (6.3)	170.2 (6.4)
Wt (kg)	68.7 (9.6)	75.5 (16.1)	76.8 (13.3)

The young subjects were recruited from the general student population at Texas Tech University and older subjects were recruited from local community. All participants were compensated for their time and effort.

Apparatus and Procedure (for more detailed description, please see Human Factors Proceeding titled: *Effects of Musculoskeletal and Sensory Degradation due to Aging on the Biomechanics of Slips and Falls*).

Treatment of Data. The converted coordinate data for each of the 26 body markers (defining a 14-segment whole body model [MacKinnon and Winter, 1993]) and the ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (Winter, 1990). Residual analyses of the difference between the filtered and unfiltered signals over three different cutoff frequencies (6, 10, and 12 Hz) determined 6 Hz as the preferred cutoff frequency. The dependent measures (vinyl tiles only), adjusted RCOF (ARCOF), slip distance (SD), sliding heel velocity (SHV), heel acceleration, and estimated center of gravity velocity of the whole body (COGV) during slipping were analyzed by 3 x 2 (age x load) two-way repeated measures analyses of variance with $\alpha = 0.05$. For this analysis load were treated as a within-subjects effects, while age was a between-subjects effect. The p-values in the ANOVA were adjusted for violations of the assumptions regarding the variance-covariance matrix using the Huynh-Feldt method to estimate ϵ and adjusting the degree-of-freedom accordingly (Winer et al., 1991). In addition, constant variance and normality assumptions were verified using residual analysis and normality plots. A computer algorithm was written in the C++ 6.0 to objectively determine the dependent measures.

Calculations of Dependent Measures

Figure 1 illustrates a typical slip behavior starting from the heel contact point. Heel contact was defined as the time when the vertical ground reaction force (GRF) exceeded 10N (to synchronize kinetic and kinematic variables, a LED was coupled to the vertical force output of the force plates, when the force exceeded 10N, a LED was triggered).

Initially, as indicated by horizontal heel positions, the heel does not slip forward (horizontal heel velocity decreases as the heel quickly decelerates during this time period). This is (no slip) believed to be the result of the position of the whole body COG (closer to the other stance foot) (MacKinnon and Winter, 1993) during the heel contact phase of the gait cycle.

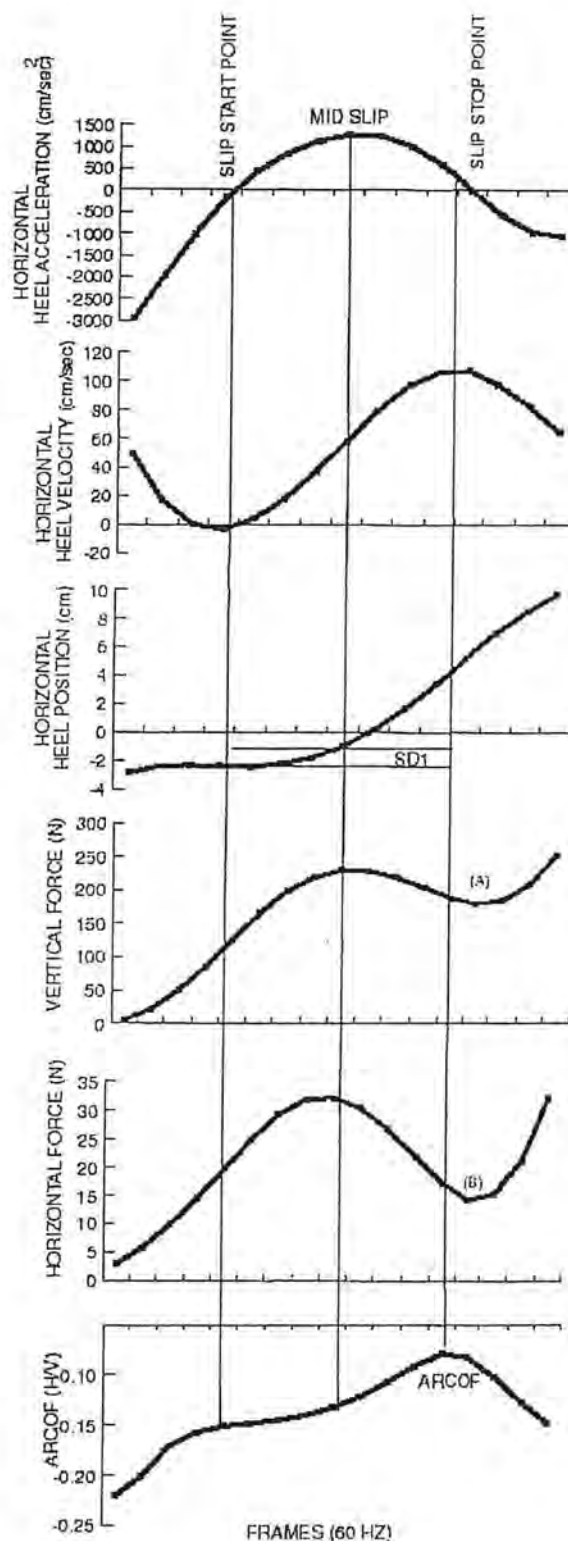


Figure 1. Composite view of the gait parameters.

Shortly after heel contact (approx. 60 ms) (as the fore foot comes down and COG shifts towards the sliding heel), heel begins to slip forward. Afterwards, sliding heel reaches maximum velocity. During this slipping period, the heel accelerates reaching the maximum near the mid point of the sliding heel velocity profile.

After reaching maximum heel velocity, the sliding heel velocity decreases to minimum, halting further slipping (not complete on the Figure 1).

Slip Distance. Strandberg and Lanshammar (1981) identified slips by examining the coordinates of the heels. They defined the skid start as the first minimum in heel forward velocity, however, they did not mention how to determine slip stop point. Perkins (1978), also did not specify how to determine the slip stop and slip start, instead presented multi-image photograph of heel slip using a stroboscope. Son (1990), utilizing 3-d coordinates of the reflectors on the subjects, identified slip start as the point at which a change in the horizontal displacement continued at a constant position in the vertical axis (the first minimum of the vertical heel velocity after the heel contact the floor surface), and the slip stop as the point at which change in vertical axis occurred, without a change in horizontal axis (the first minimum of the horizontal heel velocity after slip start point). While Son's definition is much clearer than the others, we found alteration of the vertical force profile in most of our data beyond the point of maximum horizontal heel velocity. Slip and fall experiments usually require a fall arresting rig to prevent injuries. However, a fall arresting harness may affect the outcome of the slips beyond a certain point. Figure 1, illustrates this concept. Point (A) of the vertical force profile illustrates that there is a big decrease in vertical force as the subject slips (after reaching peak heel sliding velocity). This decrease in vertical force may have resulted when the subject tried to compensate for a slip by utilizing the fall arresting harness, and in the process also, may have affected the horizontal force profile (point B). Thus, beyond the peak heel velocity point, the fall arresting harness may affect the biomechanical parameters of slip severity (such as slip distance, slipping velocity etc).

Utilizing the above concept, we defined the slip start point as the time where the first minimum of the vertical heel velocity after the heel contact occurred (a non-rearward positive acceleration-due to the slight rearward displacement occurring after the heel contact), and slip stop point as the time where the first maximum of the horizontal heel velocity after slip start point occurred (point before deceleration, Figure 1).

Adjusted Required Coefficient of Friction (ARCOF). ARCOF is the measured ratio of the horizontal foot force to the vertical foot force at the slip-stop point and represents the ability to adjust dynamic frictional requirements during slipping. The significance of this ratio is that it indicates where in the gait profile compensation for a slip is most likely occur. Figure 1 illustrates this concept. As the horizontal heel velocity reaches maximum, horizontal force is decreased (slight decrease in vertical force as well), thus,

the ratio of horizontal to vertical force profile decreases. At this point, if ARCOF is higher than the available dynamic coefficient of friction (ADCOF), the heel will continue to increase in velocity, however, on this data, ARCOF is lower than the ADCOF, and the horizontal heel velocity decreases (beginning of halting a slip).

Sliding heel velocity. The relative sliding heel velocity (SHV) of the heel after heel contact was calculated by averaging the velocity of the heel during the slip start and slip stop points.

Heel acceleration. The relative heel acceleration (Hacc) of the heel after heel contact was calculated by averaging the acceleration of the heel during the slip start and slip stop points.

Center-of-gravity (COG) velocity. The estimated whole body horizontal COG velocity during slipping (slip start and slip stop point) was calculated utilizing 14 segment whole body model defined by MacKinnon and Winter (1993).

RESULTS

Lockhart (1997) reported that elderly individuals could not reduce the adjusted RCOF (ARCOF) to available dynamic COF as well as younger subjects on slippery floor surfaces (oily vinyl tile). Consistent with previous findings, older individuals ARCOF was significantly higher than younger counterparts ($F(2,39) = 13.434, p = 0.0001, \epsilon = 1.053$). Table 2 summarizes the mean values and standard deviations for each of the dependent measures as a function of age.

The horizontal distance traveled by the foot (SD) after the heel contact phase of the gait cycle was measured utilizing heel coordinates between slip-start and slip-stop points on the vinyl floor surfaces. Older individuals SD was longer on the average than the younger counterparts ($F(2,39) = 9.115, p < 0.001, \epsilon = 1.053$).

Older individuals SHV was significantly faster than younger individuals ($F(2,39) = 5.536, p < 0.007, \epsilon = 1.053$).

Older individuals heel acceleration was significantly faster than younger individuals ($F(2,39) = 5.448, p < 0.008, \epsilon = 1.053$).

Older individuals COGV was significantly slower than the younger counterparts ($F(2,39) = 3.632, p < 0.035, \epsilon = 1.053$).

Table 2. Summary of the gait parameters.

Variables	Young Mean (S.D.)	Middle Mean (S.D.)	Elderly Mean (S.D.)
ARCOF (vinyl)	.074 (.01)	.10 (.01)	.12 (.01)
SD (cm)	4.98 (4.8)	7.65 (4.9)	11.80 (9.4)
SHV (cm/s)	44.05 (35.1)	63.95 (31.7)	74.14 (39.7)
COGV (cm/s)	115.9 (17.4)	123.2 (20.4)	107.3 (16.7)
Hacc (cm/s ²)	609.5 (79.2)	907.8 (73.5)	912.1 (66.6)

DISCUSSION

This research project was undertaken in part to establish a more robust definition of slip severity and, to provide better understanding of dynamics of slips and falls among different age groups. To do this, we compared velocity of COG of the whole body during slip, and sliding heel velocity to identify falls associated with slipping (fall index - whenever the average SHV was greater than the average COGV a fall was defined). The result of fall index is illustrated on Figure 2.

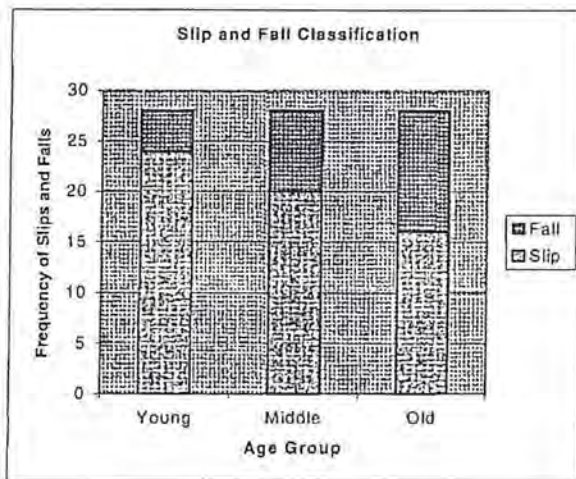


Figure 2. Frequency of slips and falls among different age groups.

Utilizing the fall index and comparing with newly defined slip definitions, we found that exceeding certain limits of SHV, SD1 (slip distance between slip start and peak acceleration point [mid slip on Figure 1]) and heel acceleration resulted in falls (Table 3).

Table 3. Slip recovery index across three age groups.

	SHV(cm/s)	SD1 (cm)	Hacc (cm/s ²)
Young	144.45	3.91	1580
Middle	145.26	3.80	1310
Old	107.63	3.12	1220

In general, when the subjects in each age group exceeded the recovery index limits, a fall resulted. The younger individuals recovery index was higher on the average and suggest that the recovery index (or slip severity) is not all same for the different age groups. Thus, in a given situation, the older individuals are at a higher risk for fall accidents. This result is further supported by higher ARCOF. On the average, the younger individuals ARCOF (.074) was adjusted within the dynamic friction requirements (.08). However, on the average, middle (ARCOF - .10) and older

individuals (ARCOF - .12) could not. Consequently, the result was longer slip distance and increased frequency of falls.

Acknowledgements

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Age effects of horizontal heel contact velocity and initiation of slips and falls.

(To be submitted to *Human Factors*)

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Keywords: Slips and Falls; Biomechanics; Aging; Horizontal Heel Contact Velocity; Sliding Heel Velocity; Friction Demand; Gait Adaptation; Slip Distances; Fall Index; Slip Recovery Threshold.

A laboratory study was conducted to investigate the process of inadvertent slips and falls among young and elderly individuals. The objective of the analysis was to examine the gait changes associated with aging (especially the higher horizontal heel contact velocity) and its effect on initiation of slips, friction demand, and frequency of falls utilizing newly defined biomechanical parameters of slips and falls. Twenty-eight subjects from two age groups (young and elderly) walked around a circular track at a comfortable pace wearing safety harnesses. Slippery floor surfaces were placed on the track over force platforms at random intervals. The results indicated that older individuals horizontal heel contact velocity was significantly faster, and friction demand was on the average higher than their younger counterparts. Additionally, older individuals slipped longer and faster, and fell more often than their younger counterparts. A comparison between fallers and non-fallers horizontal heel contact velocity indicated that in general, fallers horizontal heel contact velocity was faster than non-fallers, however, a comparison between fallers and non-fallers friction demand indicated that friction demand as measured by RCOF was not a completely deterministic predictor of actual fall events. These findings expand the long-held concept that gait changes associated with aging (especially the higher horizontal heel contact velocity) affect initiation of slip induced falls.

1. Introduction

Falls and gait instabilities are among the most serious problems facing the older population (Rubenstein, et al., 1988). Many studies have shown that with advancing age there is an increasing incidence of fatal slip and fall injuries (Agnew and Suruda, 1993, and Campbell et al., 1981). Falls are the leading cause of death resulting from injury among older people (over age 75), and the second highest cause of accidental death for 45-75 year olds (National Safety Council, 1998). The National Safety Council reported that in 1997, 14,900 Americans met their death by falling, and of these deaths, 12,000 were people over 65 years of age (National Safety Council, 1998).

A review of the biomechanical literature indicates that there are several differences in the gaits of older and younger people. Elderly people tend to walk slower, have a shorter step length and a broader walking base, which eventuates in an increase in stance time, and double support time (Murray, Kory, and Clarkson, 1969; Gillis, Gilroy, Lawley, Mott, and Wall, 1986; Imms and Edholm, 1979; and Winter, Patla, Frank, and Walt, 1990). Many researchers have observed that on slippery floor surfaces, subjects tended to shorten their step length in order to reduce foot velocities, foot shear forces and reduce the likelihood of slipping (Cooper and Glassow, 1963). As a result, the shorter step length and the slower walking velocity of elderly individuals are thought to result in a more stable or safer gait pattern, but these gait changes may have some important implications for initiation of slip induced falls.

In general, initiation of a slip occurs whenever the frictional force (F_{μ}) opposing the movement of the foot is less (due to contamination) than the shear force (F_h) of the foot after the heel contact phase of the gait cycle (Figure 1). Specifically, at the time of the heel contact, there is a forward thrust component of force on the swing foot against the floor. This results in a forward horizontal shear force (F_h) of the ground against the heel. Additionally, a vertical force (F_v) results as the body weight and the downward momentum of the swing foot (and leg) make contact against the ground. Perkins (1978) identified six peak forces in a normal gait cycle by observing ground reaction forces exerted between the shoe and ground (on non-slippery floor surface) (Figure 2), and calculating the ratio of horizontal to vertical foot forces (F_h/F_v). The significance of this ratio (F_h/F_v) is that it indicates where in the walking step a slip is most likely to occur (slip initiation). Analyzing the ratio, Perkins indicated that dangerous forward slip was most likely to occur shortly after (< 50-100 ms) the heel contact phase of the gait cycle (peak 3 in Figure 2), and termed this ratio (F_h/F_v at peak 3), "Required Coefficient of Friction" (RCOF) because the ratio represented the general friction demand (minimum coefficient of friction that must be available or "required") at the shoe-floor interface (to prevent initiation of forward slipping). Hanson, Redfern, and Mazumdar (1999) indicated that in general (although not totally deterministic), the number of slip and fall events increased as the difference between the friction demand (RCOF) and measured dynamic

COF of the floor surface increased. Walking speed, which is the product of cadence and step length, affects the magnitude of shear force (F_h), and therefore, affects the friction demand (RCOF) during locomotion (e.g., increases in walking velocity and step length in

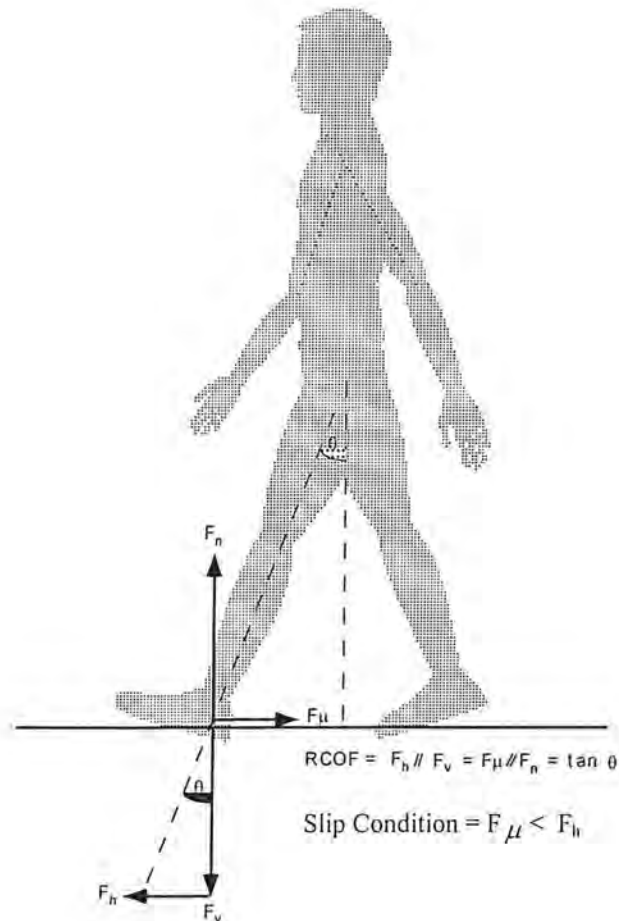


Figure 1. Force vectors applied by the left foot during the heel contact phase in normal level walking. (F_h = horizontal, F_v = vertical, F_μ = frictional, and F_n = normal force) (adapted from Grönqvist et al., 1989).

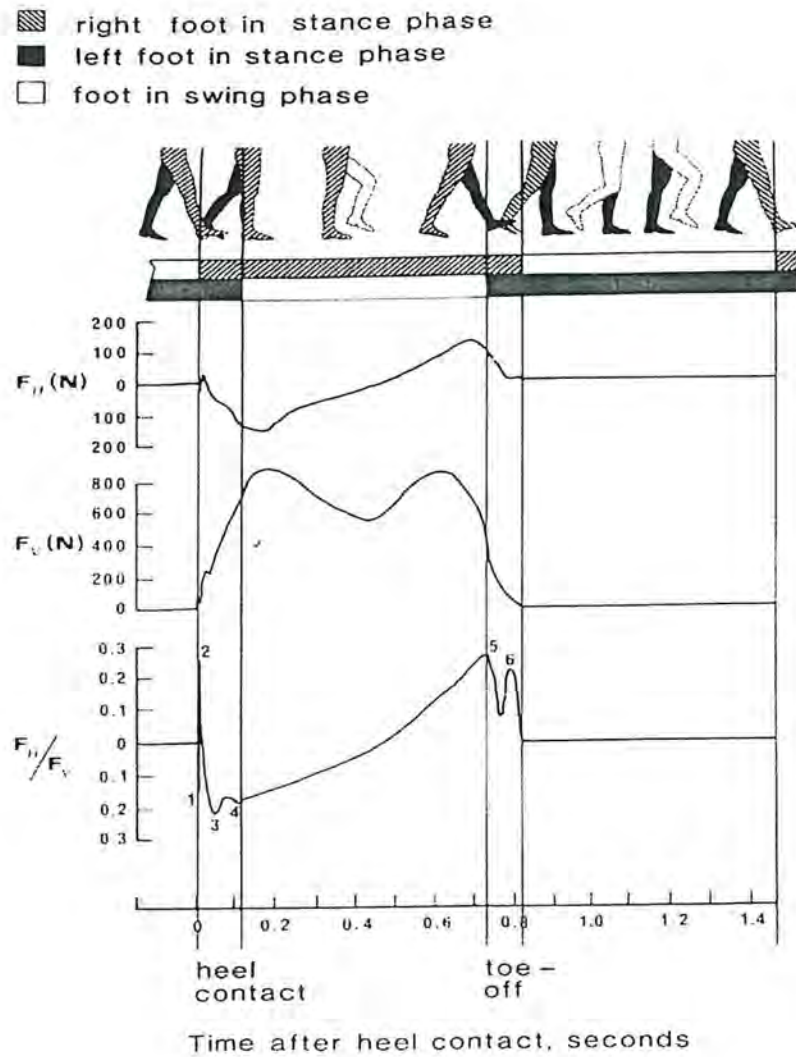


Figure 2. Gait phases in normal level walking with typical horizontal, vertical, and their ratio for one step on non-slippery surface (Perkins, 1978).

general, increases the friction demand) (Carlsöö 1962; James 1983; Soames and Richardson, 1985; and Myung et al., 1992). Figure 1 illustrates the relationship between step length and friction demand (RCOF). In terms of kinematics, RCOF has been related to the tangent of the angle between the leg and a line perpendicular to the floor (Grönqvist et al., 1989). As a result, increasing the step length will, in general, increase RCOF (Perkins, 1978; Grönqvist et al., 1989).

Utilizing above relationships between the gait parameters (walking velocity and step length) and friction demand (RCOF), the rationale for elderly individuals higher frequency of slip and fall accidents remains illusive. As indicated, many studies have observed that elderly individuals step length was shorter and walking velocity was slower than their younger counterparts. In turn, shorter step length and slower walking velocity should have decreased the friction demand and therefore, in a given situation, elderly individuals likelihood of slips and ultimately falls should have been reduced. These conflicting findings suggest that there might be other factor(s) (other than step length and walking velocity) contributing to elderly individuals higher frequency of slip and fall accidents.

During walking, horizontal heel velocity rises gradually after heel-off, reaches a maximum velocity late in the swing phase, and falls rapidly to near zero just prior to heel contact. The significance of the horizontal heel velocity before the heel contact phase of the gait cycle is that the horizontal heel velocity must be sufficiently reduced (as to reduce friction demand) at the end of swing phase so that a dangerous slip will not occur (or initiated). Winter et al. (1990) and Lockhart (1997) reported that the horizontal heel velocity during the heel contact phase of the gait cycle was significantly higher for elderly individuals than for younger individuals, even though the walking velocity of elderly subjects was slower. Winter et al. (1990) also noted that friction between the heel and the floor reduced heel velocity to zero, and cautioned against low COF floor surfaces.

Thus, general gait changes among elderly individuals, and specifically, higher horizontal heel contact velocity during the critical phase of the gait cycle may increase the potential for slip-induced falls if the friction between the heel and the floor is reduced due to contamination of the floor surface.

Although much has been learned over the last few decades about the gait changes (e.g., shorter step length, and slower walking velocity but higher horizontal heel contact velocity) among elderly individuals, still little is known about how these intrinsic changes affect initiation of slips and ultimately falls. In addition, although linear implication was made between the increase in friction demand (RCOF) and increase in fall frequency, this relationship may not be linear (e.g., higher friction demand may not be associated with increase in number of actual falls) (Strandberg and Lanshammar, 1985, and Harris and Shaw, 1988).

In general, the objective of this analysis was to investigate the process of inadvertent slips and falls among young and elderly individuals. More specifically, this analysis presents a dynamic gait control strategy employed by both young and elderly individuals during ambulation over slippery and non-slippery floor surfaces that addresses following questions: (1) Does (especially the elderly individuals) higher horizontal heel contact velocity affect initiation of slips and ultimately falls? (2) Is there a correlation between friction demand as measured by RCOF and frequency of falls (in other words, do people with higher RCOF fall more often than the people with lower RCOF)? Utilizing repeatable biomechanical patterns associated with slipping, a method was developed to quantify the performance of initiation of slips and frequency of actual falls. To investigate the relationship between the horizontal heel contact velocity and the initiation of actual slips, a slip parameter, "initial slip distance," was developed and explored during walking on the oily vinyl floor surface. Additionally, a "fall index" was developed and explored to investigate the relationship between distance slipped and frequency of actual falls. Furthermore, friction demand (RCOF) was observed on the carpeted floor surface to elaborate on the relationship between friction demand (RCOF) and horizontal heel contact velocity, and fall frequency.

In this analysis, the focus is limited to the age differences in gait parameters and its relationship between dynamics of slips and falls during an un-laden state. It was hypothesized that gait changes among elderly individuals, specifically higher horizontal heel contact velocity, would affect severity of initiation of slips and ultimately falls more than their younger counterparts. This research will provide a better understanding of the gait characteristics of elderly versus young age groups as they walk on slippery and non-

slippery floor surfaces. Although epidemiological studies on slip and fall accidents reveal higher incidence of fatal injuries among older individuals, still little is known about the relationship between age-related factors and slip and fall accidents. In general, this information will help pinpoint useful fall related predictors and allow engineers to design better work environments as well as jobs to reduce the incidence of slips and falls among aging population and workforce.

2. Method

2.1. Subject population

Fourteen young individuals (7 male and 7 female) and 14 elderly individuals (7 male and 7 female) participated in this experiment. Subject's age, height and weight information is presented in Table 1. The young subjects were recruited from the general student

Table 1. Subject information

	Young (18-29 yrs.) Mean (S.D.)	Old (65 yrs. and over) Mean (S.D.)
Age (yr)	22.6 (2.1)	75.5 (6.8)
Ht (cm)	169.7 (6.1)	170.2 (6.4)
Wt (kg)	68.7 (9.6)	76.8 (13.3)

population at Texas Tech University and older subjects were recruited from the local community. All participants were compensated for their time and effort.

2.2. Apparatus

Two commonly used floor materials were used in this experiment: outdoor carpet (Beau Lieu ¼" Olefin) and vinyl tile (Armstrong). The vinyl tile surface was covered with motor oil (10W40) to reduce the coefficient of friction (COF). The available dynamic COF (ADCOF) for each surface was measured using a standard 4.54 Kg (10 lb.) horizontal pull slipmeter with a rubber sole material on the force platform and found to be 1.80 for the outdoor carpet and 0.08 for the oily vinyl tile. Walking trials were

conducted on a circular track (20 meter in circumference) using an overhead fall arresting rig as shown in Figure 3. The wooden deck was approximately 6.7 meters x 6.7 meters. The entire deck was covered with outdoor carpet. A remote controlled floor changer (RCFC) was used to change the test floor surfaces so as to provide unexpected slippery conditions. The RCFC unit was composed of a DC motor (LEESON Electric Corp.) and a gliding shaft (ACME Thread) attached to a platform. A remote control unit controlled the DC motor. Once triggered, the DC motor turned the ACME thread (max. 1750 rpm) thereby, moving the platform to a desired floor level. The test surfaces were mounted on a platform, which was connected to the force plates. The overall function of the system allowed a subject to walk under experimental conditions without being aware of the floor surface change. A fall arresting rig was used to protect subjects from falling during the experiment. The rig consists of a full-body parachute harness attached to an automated overhead suspension arm. A feedback control system allowed the arm to sense the position of the subject and increase or reduce velocity to stay overhead. The rig was designed to permit the subject to fall approximately 15 cm before arresting the fall and stopping the forward motion. An Ariel Performance Analysis System (APAS) and four Panasonic video recorders (CCD) were used to collect the three-dimensional posture data of the subjects as they walked over the test surface. Posture data were sampled and recorded at a rate of 60 Hz. The ground reaction forces of the subjects walking over the test surfaces were measured using two Bertec force plates also sampled at a rate of 60 Hz.

2.3. Procedure

The subjects were scheduled to participate in two testing sessions within one week's time. The subjects attended a familiarization session before the walking experiment. During the familiarization, the fall arresting system and walking conditions were introduced. During the experiment, the subjects walked across the carpeted floor surface (base line floor) for 10 minutes without the load. Within the 10 min session, 2 slippery conditions were randomly introduced by the system, and measurements of subject's posture and ground reaction forces were recorded (the second trial was used only if the first trial was not acceptable [for example, stepping on the edge of the force platform]). While walking, subjects were instructed to focus their eyes on a light emitting diode

located approximately 2 meters above and 3 meters away from the testing area. A secondary task that required them to call out when the light was on and when it was off was used to ensure that they attended to the LED. In addition, two floor changers randomly distributed locations of the slippery floor surfaces (e.g. two force plate locations). Standard shoes with rubber soles were supplied to all subjects to maintain a

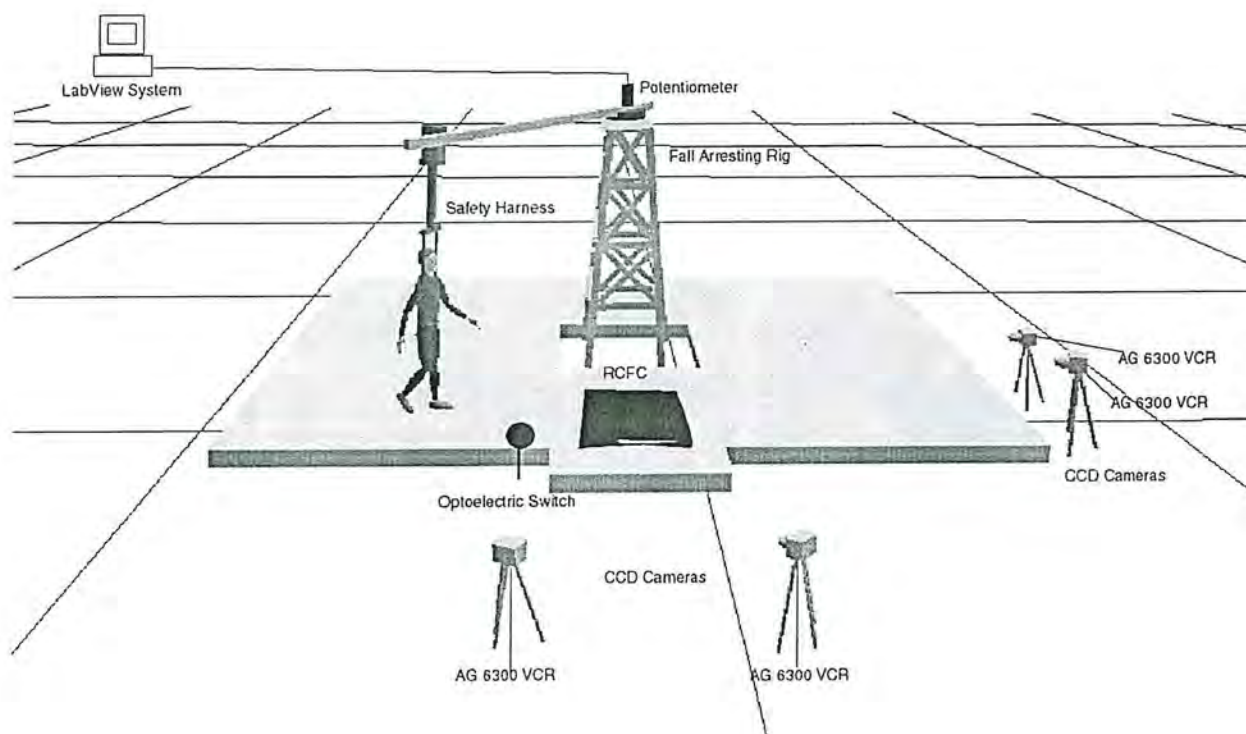


Figure 3. Field layout of the experiment including; fall arresting rig, potentiometer interfaced with the LabView system, safety harness, force platforms, optoelectric switch, CCD cameras (4), AG 6300 VCR (4) and Remote Control Floor Changer (RCFC) Units with base line carpet floor material.

constant COF level. Subjects were also supplied with a Walkman (listening to old comedy routines) during the walking experiment to conceal any sound of the floor changer's motors.

2.4. *Calculations of Dependent Measures*

The converted coordinate data from APAS were used to calculate the gait parameters (step length, horizontal heel contact velocity, initial slip distance [SDI], slip distance II [SDII], sliding heel velocity [SHV], and walking velocity [velocity of whole body COG]).

The converted coordinate data from APAS and ground reaction forces were observed during a typical slip behavior to provide robust definitions of the gait parameters. Figure 4 illustrates a typical slip behavior starting from the heel contact point. Heel contact was defined as the time when the vertical ground reaction force (GRF) exceeded 10N (to synchronize kinetic and kinematics variables, an LED was coupled to the vertical force output of the force plates, when the force exceeded 10N, an LED was triggered).

Initially, as indicated by the horizontal heel position (Figure 4 c), the heel does not slip forward (horizontal heel velocity decreases [Figure 4 b] as the heel quickly decelerates [Figure 4 a] during this time period). Shortly after heel contact (approx. 60 ms) (as the fore foot comes down and COG shifts towards the sliding heel), the heel begins to slip forward (Figure 4 c). Afterwards, sliding heel reaches peak sliding heel velocity (PSHV) (Figure 4 b). During this slipping period, the heel accelerates reaching the maximum (Figure 4 a) near the mid point of the sliding heel velocity profile (Figure 4 b).

After reaching maximum heel velocity, the sliding heel velocity decreases to minimum, halting further slipping (not completed on the Figure 4). axis (the first minimum of the vertical heel velocity after the heel contact the floor surface), and the slip stop as the point at which change in vertical axis occurred, without a change in horizontal axis (the first minimum of the horizontal heel velocity after slip start point). Although Son's definition is much clearer than the others, an alteration of the vertical force profile in most of the data beyond the point of maximum horizontal heel

velocity was observed in this experiment. Alteration of the vertical force may have occurred due to the use of the fall arresting rig by the subjects beyond a certain slip distance. Figure 4, illustrates this concept. Point (P1) of the vertical force profile illustrates that there is a significant decrease in vertical force (Figure 4 d) as the subject slips (after reaching peak sliding heel velocity). This decrease in vertical force may have resulted when the subject tried to compensate for a slip by utilizing the fall arresting harness, and in the process also, may have affected the horizontal force profile (point (P2) on Figure 4 e). Thus, beyond the peak heel velocity point, the fall arresting harness may affect the biomechanical parameters of slip severity (such as slip distance, slipping velocity etc).

2.4.1. *Initial Slip Distance (SDI)*: Initial slip distance (SDI) (the resultant distance traveled by the foot after the heel contact phase of the gait cycle) was measured to provide information concerning the severity of initiation of slips. Utilizing above concept, slip-start point was defined as a point where non-rearward positive acceleration of the foot after heel contact occurred (where the first minimum of the vertical heel velocity after the heel contact occurred), and slip-stop point for SDI was defined as a point where peak heel acceleration occurred after slip-start point (mid slip on Figure 4a). Thus, SDI was calculated using the heel coordinates between slip-start (X_1, Y_1) and slip-stop (X_2, Y_2) points on the vinyl floor surface, and using the formula:

$$SDI = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

2.4.2. *Slip Distance II (SDII)*: Slip distance II (SDII) was measured to provide information concerning the slip behavior after the initiation of slips. The start point for the Slip distance II (SDII) was defined as a SDI slip-stop point (peak heel acceleration – mid slip on Figure 4a), and the end of slip (for the purpose of calculation) as the time where the first maximum of the horizontal heel velocity after slip start point occurred (point before deceleration (PSHV), Figure 4a and 4b). Additionally, SDII was calculated using the heel coordinates between slip-start (X_1, Y_1) and slip-stop (X_2, Y_2) points on the vinyl floor surface for SDII, and using the formula:

$$SDII = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

2.4.3. *Sliding Heel Velocity (SHV)*: The relative sliding heel velocity (SHV) of the heel after heel contact was calculated (assess severity of slips and falls) by averaging the velocity of the heel during the slip start point and PSHV points (Figure 4a) and using the formula:

$$ISHV_{k+i} = [X_{(k+i+1)} - X_{(k+i-1)}] / 2\Delta t$$

where, k = slip start point
and i = slip frames

thus,

$$SHV = \sum_{i=1}^N ISHV_{k+i} / N$$

where, N = total slip frames

2.4.4. *Step Length (SL)*: The linear distance in the direction of progression between successive points of foot-to-floor contact of the first foot (X_1, Y_1) and other foot (X_2, Y_2) was measured. The step length was calculated from the difference between consecutive positions of the heel contacting the floor (resultant) using the formula:

$$SL = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

2.4.5. *Step Length Index (SLI)*: Normalized step length index was calculated by using the formula:

$$SLI = SL / Ht$$

where, Ht = height of each subject.

2.4.6. *Heel Velocity (HV)*: The instantaneous horizontal heel velocity (HV) at heel contact was calculated utilizing the heel velocities in horizontal direction at the foot displacement of 1/60 second before and after the heel contact phase of the gait cycle using the formula:

$$HV = [X_{(i+1)} - X_{(i-1)}] / 2\Delta t$$

2.4.7. *Friction Demand (RCOF)*: The required coefficient of friction (RCOF) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force (F_H/F_V) after heel contact (peak 3 as defined by Perkins, 1978) on the carpeted floor surface to obtain the friction demand.

2.4.8. *Horizontal (plane of progression) Velocities (before and after heel contact) of the Whole Body Center-of-Gravity*: A sagittal 3-D link (14) segment model was used to calculate position and velocities of the COG. The sagittal and frontal models utilized the 14-component link-segment system defined by MacKinnon and Winter, 1993, and the anthropometric model (Winter, 1990) (for a detailed discussion of the modeling method, see MacKinnon and Winter, 1993). Several assumptions were required to compute estimates of the COG. The assumptions included: (a) the human body can be represented by a set of 14 rigid bodies; (b) the center of mass of each segment is represented by a single point and its location remains fixed relative to the segment; (c) the anthropometric information used for the segment weights are representative of the body weights of interest; (d) the limbs move about fixed points when the body changes position; (e) the limbs are connected by massless hinge joints.

In general, utilizing the definition of COG, a whole body center-of-gravity was calculated by summing the moment of the whole body about the same axis assuming uniform density:

$$MX = \sum_{i=1}^{14} m_i x_i$$

where m_1, m_2, \dots, m_{14} were the masses of the 14 segments; M was the mass of the body; and x_1, x_2, \dots, x_{14} were the respective distances of the center-of-gravity of the segments and whole body from the reference point. Therefore,

$$X = \frac{1}{M} \sum_{i=1}^{14} m_i x_i$$

2.4.8A. *Velocity of COG Before Heel Contact (COGVB)*: The relative horizontal COG velocity of the whole body was calculated by averaging displacement over 3 time interval (50 ms) of the instantaneous velocity of the COG before the heel contact phase of the gait cycle using the formula:

$$\text{ICOGVB}_{k-i} = [X_{(k-i+1)} - X_{(k-i-1)}] / 2\Delta t \quad \text{where, } k = \text{heel contact frame}$$

thus,

$$\text{COGVB} = \sum_{i=1}^N \text{ICOGVB}_{k-i} / N \quad \text{where, } N = \text{total frames (3)}.$$

2.4.8B. *Velocity of COG After Heel Contact (COGVA)*: The relative horizontal COG velocity of the whole body was calculated on the oily vinyl floor surface to identify a fall ($\text{SHV} > \text{COGVA}$) by averaging the velocity of the COG during the slip start point and PSHV points (period of slip) and using the formula:

$$\text{ICOGVA}_{k+i} = [X_{(k+i+1)} - X_{(k+i-1)}] / 2\Delta t \quad \text{where, } k = \text{slip start point}$$

and $i = \text{slip frames}$

thus,

$$\text{COGVA} = \sum_{i=1}^N \text{ICOGVA}_{k+i} / N \quad \text{where, } N = \text{total slip frames}$$

2.5. Treatment of Data

The converted coordinate data for each of the 26 body markers (defining a 14-segment whole body model [MacKinnon and Winter, 1993]) and the ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (Winter, 1990). Residual analyses of the difference between the filtered and unfiltered signals over three different cutoff frequencies (6, 10, and 12 Hz) determined 6 Hz as the preferred cutoff frequency.

The dependent measures step length (SL), step length index (SLI), horizontal heel contact velocity (HV), and walking velocity (as measured by whole body COG-before heel contact [COGVB]) were analyzed using a 3 x 2 (age x floor) two-way repeated

measures analyses of variance (ANOVA); RCOF was analyzed using an one-way analysis of variance on the carpeted floor surface; initial slip distance (SDI), slip distance II (SDII), and sliding heel velocity (SHV) were analyzed using one-way analyses of variance on the oily vinyl tile floor surface with $\alpha \leq 0.05$. For these analyses floor (where applicable) was treated as a within-subjects effect, while age was a between-subjects effect. In addition, bivariate correlation analysis was performed to describe the relationships (actual slip) between the independent (HV) and dependent variables (SDI, SDII, and SHV) on the oily vinyl floor surface. Furthermore, a fall index was developed utilizing sliding heel velocity (SHV) and velocity of whole body COG after heel contact (COGVA) on the oil vinyl floor surface (a fall was defined as $SHV > COGVA$).

The p-values in the repeated measures ANOVA were adjusted for violations of the assumptions regarding the variance-covariance matrix using the Huynh-Feldt method to estimate ϵ and adjusting the degree-of-freedom accordingly (Winer et al., 1991). In addition, constant variance and normality assumptions were verified using residual analysis and normality plots. A computer algorithm was written in the C++ 6.0 to objectively determine the dependent measures.

3. Results

3.1. *Stride Length and Stride Length Index*

The step length and step length index were analyzed on both (slippery and non-slippery) floor surfaces to observe age related gait changes as well as to assist in the determination of a base line assumption on inadvertency (previous non-inadvertent experiment findings suggest that when walking on the slippery floor surfaces subjects tended to reduce their step length).

Consistent with previous findings (Imms and Edholm (1979); Bassegy et al. (1976), Winter (1991), and Lockhart (1997)), a reduction in step length was observed for the elderly individuals. In general, the result of two-way ANOVA indicated statistically significant ($p \leq 0.05$) SL differences between the age groups ($F_{(1,26)} = 5.307, p \approx 0.029, \epsilon = 1.04$). Similarly, the ANOVA analysis of SLI also showed significant effects for the age groups ($F_{(1,26)} = 8.605, p \approx 0.007, \epsilon = 1.04$). Additionally, there were no statistically

significant ($p > 0.05$) floor effects on SL ($F_{(1,26)} = 1.859, p \approx 0.1844, \varepsilon = 1.04$) and SLI ($F_{(1,26)} = 1.642, p \approx 0.211, \varepsilon = 1.04$). The overall step length on the carpeted floor surface was only slightly longer (less than 1cm) than the oily vinyl floor surface (compared to the previous non-inadvertent experiment where step length difference between slippery and non-slippery floor surfaces was greater than 10 cm [Lockhart, 1997]). Lack of significant SL and SLI difference between slippery and non-slippery floor surface suggest that subjects were not aware of the floor changes and thus did not alter their step length when stepping on the slippery floor surface.

Table 2 summarizes the mean values and standard deviations for each of the dependent measures as a function of age.

Table 2. Summary of Gait Parameters.

Variables	Young		Elderly	
	Mean	(S.D.)	Mean	(S.D.)
Step L (cm)	65.35	(7.45)	58.87	(7.93)
SL Index	.387	(.04)	.345	(.03)
HV (cm/s)	27.09	(14.52)	39.21	(17.93)
COGVB (cm/s)	109.99	(14.42)	99.87	(16.51)
*RCOF	.177	(.02)	.187	(.02)
**SDI (cm)	1.09	(.39)	2.17	(.36)
**SDII (cm)	4.25	(.87)	7.67	(.93)
**SHV (cm/sec)	47.34	(9.74)	75.84	(9.86)

* Measured on carpeted floor surface only.

** Measured on oily vinyl floor surface only.

3.2. Heel Velocity and Walking Velocity (COGVB)

The result of two-way ANOVA indicated that the elderly individuals horizontal heel contact velocity (HV) was significantly ($p \leq 0.05$) faster than their younger counterparts ($F_{(1,26)} = 5.076, p \approx 0.033$) even though the walking velocity (COGVB) of elderly individuals was significantly slower than their younger counterparts ($F_{(1,26)} =$

4.404, $p \approx 0.045$). Additionally, there were no statistically significant ($p > 0.05$) floor effects on HV ($F_{(1,26)} = 1.767$, $p \approx 0.1953$) and COGVB ($F_{(1,26)} = 1.906$, $p \approx 0.1792$).

3.3. Friction Demand (RCOF)

RCOF was calculated only on the non-slippery (carpeted) floor surface due to the alteration of “Peak 3” ratio during ambulation over the slippery (vinyl) floor surface.

Although elderly individuals mean friction demand (RCOF) was higher than their younger counterparts, the one-way ANOVA analysis of RCOF indicated no statistically significant difference between the age groups ($F_{(1,26)} = 1.763$, $p < 0.1958$).

3.4. Slip Distances (SDI and SDII)

Elderly individuals initial slip distance (SDI) was significantly longer than their younger counterparts ($F_{(1,26)} = 4.075$, $p < 0.05$). Additionally, the elderly individuals slip distance II (SDII) was significantly longer than their younger counterparts ($F_{(1,26)} = 7.18$, $p < 0.013$).

3.5. Sliding Heel Velocity (SHV)

Sliding heel velocity was quantified during slipping on the oily vinyl floor surface to provide information concerning the severity of slips and falls (utilized for quantifying actual falls). The one-way ANOVA analysis of SHV indicated that the elderly individuals sliding heel velocity (SHV) was significantly faster than their younger counterparts ($F_{(1,26)} = 4.221$, $p < 0.05$). Figure 5 illustrate the results of individual trials and mean value (darker line) of heel velocity before heel contact (HV) and after heel contact (SHV) among young and elderly individuals on the oily vinyl floor surface.

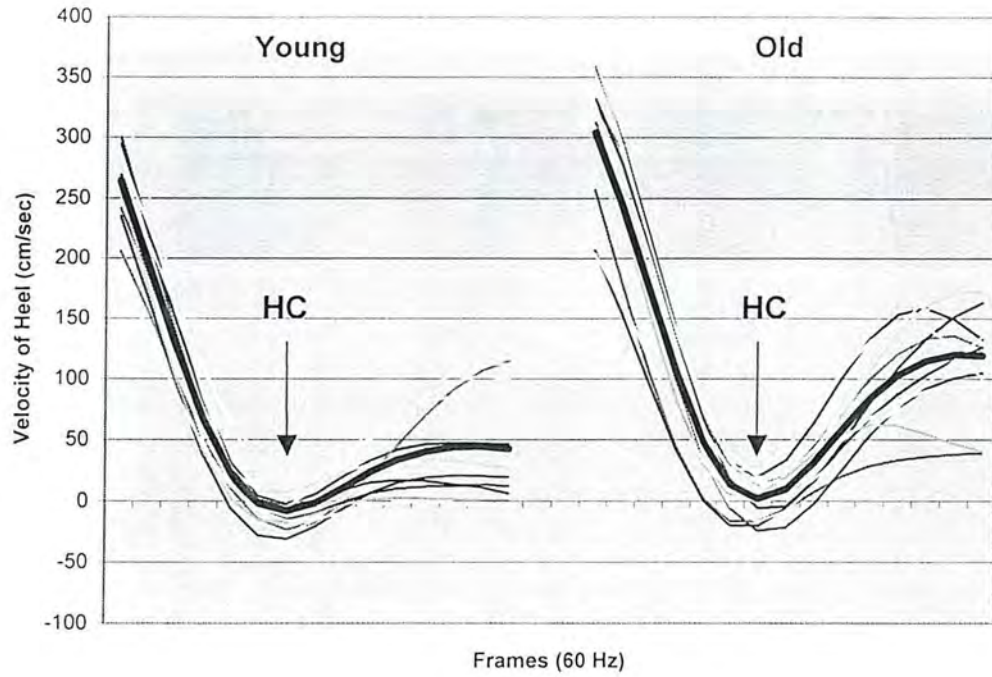


Figure 5. Composite pattern of young and older individuals heel velocity before heel contact (HV) and after heel contact (SHV) (7 frames before and 7 frames after heel contact) on oily vinyl floor surface (including the heel contact frame [HC]). The darker line expresses the average pattern of the heel velocities.

3.6. Frequency of Actual Falls (Fall Index)

Fall Index was obtained by comparing horizontal COGVA of the whole body with sliding heel velocity (SHV) of the individuals on the oily vinyl floor surface (during the period of slipping). In order to objectively assess an actual fall, a fall was identified as whenever the SHV was greater than the COGVA during slipping.

In addition, visual inspections of video recordings of the actual fall trials (as defined by Fall Index) were made to ensure that actual falls occurred. The result of the Fall Index indicated that younger individuals (2 subjects) fell total of two times (out of total of 14 trials), and elderly individuals (7 subjects) fell total of 7 times (out of total of 14 trials).

3.7. Slip Recovery Threshold

In addition, utilizing the Fall Index and comparing with newly defined slip parameters (SHV and SDI), exceeding certain limits of SHV and SDI resulted in falls (Table 3). The result of Slip Recovery Threshold indicated that the younger individuals recovery threshold was higher on the average and suggests that the recovery threshold is not all same for the entire population. Thus, in a given situation, the older individuals are at a higher risk for fall accidents (e.g., younger individuals can slip longer and faster and not fall).

Table 3. Slip Recovery Threshold across two age groups.

	SDI (cm)	SHV (cm/sec)
Young	3.91	144.45
Old	3.12	107.63

3.8. Relationship Between the HV and Initial Slip Distance (SDI)

The relationship between HV and initial slip distance (SDI) was observed to indicate (and quantify) effects of horizontal heel contact velocity on initiation of slips. The result of correlation analysis indicated statistically significant relationship between HV and SDI ($p \approx 0.0001$) with $R^2 = .41$ (Figure 5). This result suggests that individuals with higher horizontal heel contact velocity slipped longer initially.

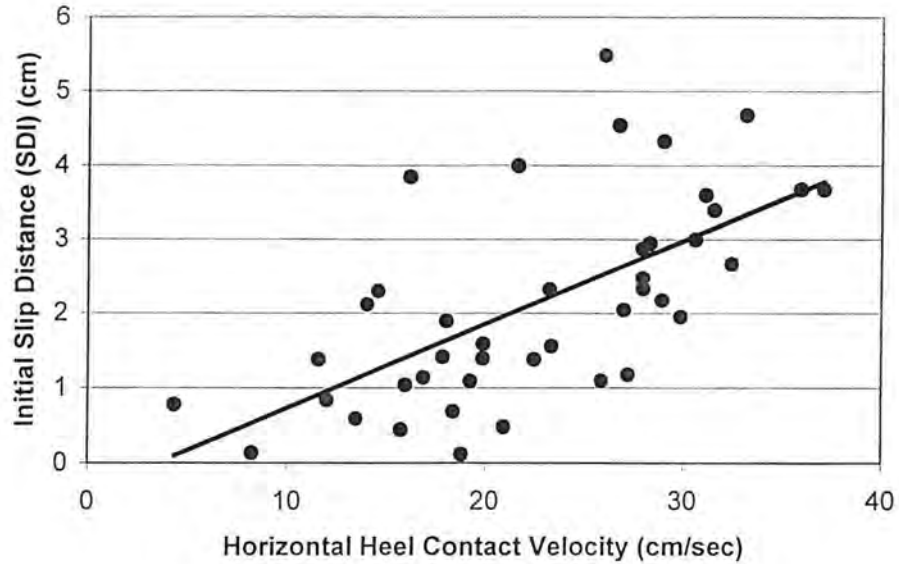


Figure 5. Correlation between initial slip distance (SDI) and horizontal heel contact velocity on the oily vinyl floor surface. Relatively high R^2 (.41) value indicates that higher heel contact velocity increased severity of slip initiation as defined by initial slip distance.

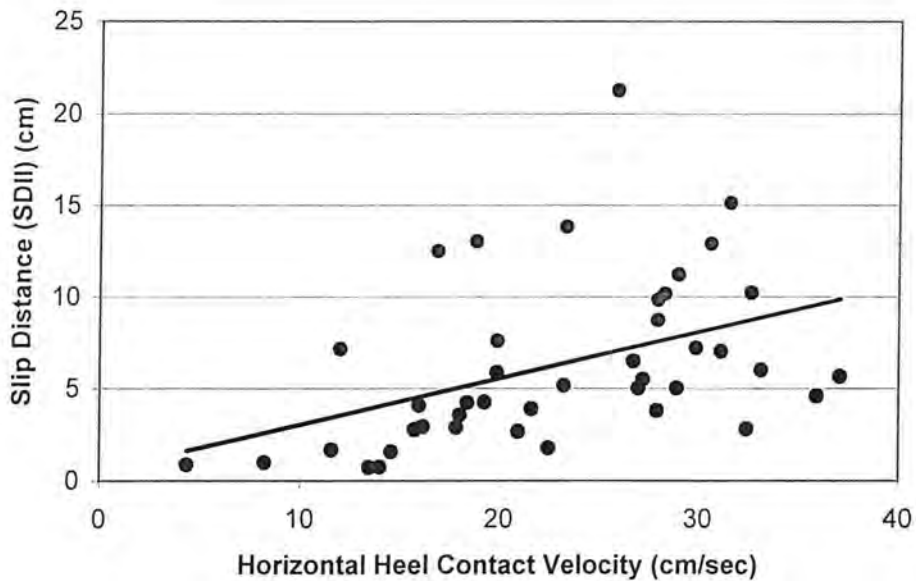


Figure 6. Correlation between slip distance II (SDII) and horizontal heel contact velocity on the oily vinyl floor surface. Relatively low R^2 (.18) value indicates that horizontal heel contact velocity may not be an only factor influencing slip distance II (SDII).

3.9. *Relationship Between the HV and Slip Distance II (SDII)*

The relationship between HV and slip distance II (SDII) was observed to investigate effects of HV on slipping behavior after the initiation of slips. The result of correlation analysis between HV and SDII indicated a statistically significant relationship ($p \approx 0.0001$), however, the relationship ($R^2 = .18$) between horizontal heel contact velocity and slip distance was lower than the relationship between HV and initial slip distance (Figure 6). This result suggests that slip distance II (SDII) maybe affected by factors other than instantaneous horizontal heel contact velocity.

3.10. *Fallers and Non-Fallers Profile of RCOF and HV*

In order to investigate the relationship between friction demand as measured by RCOF and HV, and actual fall events, a Fall Index and an individual's RCOF and HV were utilized to compare fallers and non-fallers. The results suggest that for the younger individuals, fallers RCOF was on the average was higher than the non-fallers, however, for the elderly individuals, fallers RCOF was lower than the non-fallers (Figure 7). In terms of horizontal heel contact velocity (HV), younger individuals HV was slightly faster for the fallers than the non-fallers. Additionally, for the elderly individuals, HV was faster for the fallers than the non-fallers (Figure 8). These results suggest that friction demand as measured by RCOF may not be totally deterministic predictor of actual fall events.

4. Discussion

This research project was undertaken to provide a better understanding of how gait changes and especially higher horizontal heel contact velocity among elderly individuals affect the process of initiation of inadvertent slips and ultimately falls.

In essence, the goal of this analysis was to elaborate on the primary and secondary risk factors associated with slipping accidents. Primarily, most slipping accidents occur inadvertently when the individual is unaware of the hazards associated with floor contamination. In such cases a person may be quite unprepared for corrective gait adaptations due to the rapid change in floor COF (Grönqvist, 1995). The method developed in present study is designed particularly for assessing these types of critical

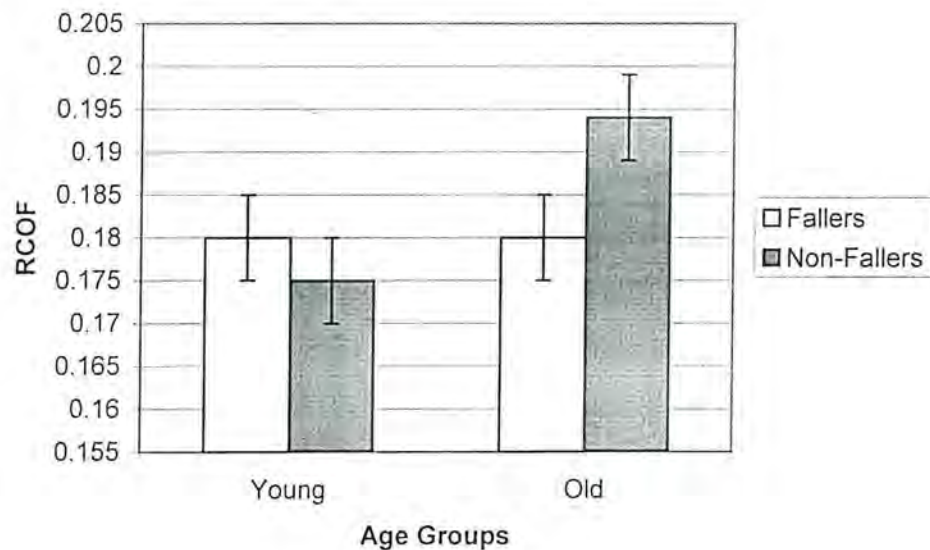


Figure 7. Comparison of fallers and non-fallers RCOF profile between young and older age groups.

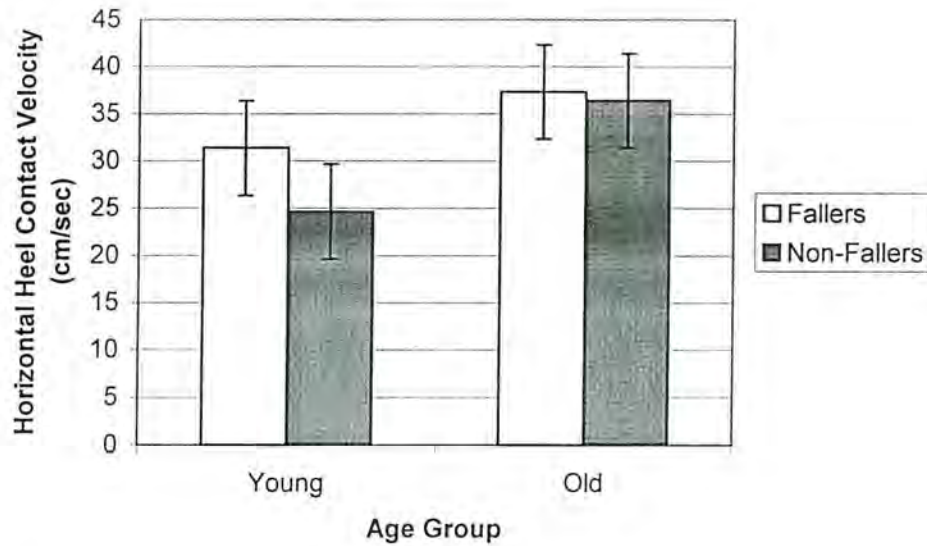


Figure 8. Comparison of fallers and non-fallers HV profile between young and older age groups.

situations. In addition, a secondary risk factor associated with aging (such as gait changes among older individuals and severity of slips and falls) was elaborated in this study.

Consistent with previous findings (Winter et al., 1990; Lockhart, 1997) older individuals step length was shorter, and horizontal heel contact velocity was significantly faster than their younger counterparts even though the walking velocity was significantly slower. Although shorter step length and slower walking velocity of older individuals should have resulted in lower friction demand at the time of heel contact due to the decrease in magnitude of the horizontal ground reaction force when walking with shorter stride length and slower walking velocity (Perkins, 1978; Soames and Richardson, 1985), a base-line experiment on the carpeted floor surface indicated that the elderly individuals friction demand was on the average higher (somewhat due to the higher horizontal heel contact velocity) than their younger counterparts. Thus, in a given situation, older individuals are placed at a higher risk for initiation of slips than their younger counterparts. This statement is further supported by the relationship between initial slip distance (SDI) and horizontal heel contact velocity (HV). The correlation ($R^2=0.41$) between SDI and HV indicated that individuals with higher horizontal heel contact velocity slipped longer initially. Furthermore, the result of the age effect on SDI indicated

that the initial slip distance of elderly individuals was significantly longer than their younger counterparts. Thus, it seems that higher heel contact velocity of older individuals will increase the risk associated with initiation of slips.

In terms of falling frequencies, the result of Fall Index indicated that older individuals fell considerably more than their younger counterparts. Relatively low correlation between HV and SDII ($R^2=0.18$) indicated that horizontal heel contact velocity was not the only deterministic factor influencing SDII. SDII has been related to the beginning of the recovery phase of the slips and falls (Lockhart et al., 2000a). Thus it seems that factors influencing the recovery phase of the slips and falls (muscular strength and sensory information, Lockhart et al., 2000b) may influence SDII more than initial horizontal heel contact velocity. Furthermore, as suggested by Hanson et al., (1999) friction demand (RCOF) may not be a totally deterministic factor influencing actual fall events. This statement is further supported by the fallers and non-fallers profile of RCOF. As indicated, there was a disagreement between RCOF and actual fall events (especially for the elderly individuals). Therefore, it seems that friction demand (RCOF) and horizontal heel contact velocity (HV) will influence initiation of slips, however may not be totally deterministic predictors of the actual fall events.

Previously, slip distance was classified into categories (micro, slip, slid etc.) based on the distance individuals slipped (Strandberg and Lanshammar 1981; Perkins and Wilson 1983; Leamon and Son 1989; and Leamon and Li 1990). Slip distance was thought to be directly related to the occurrence of a fall. For example, Strandberg and Lanshammar (1981) suggested that a slip was likely to result in a fall if the slip distance exceeded 10 cm in distance (categorized as sliding, Leamon and Li, 1990). However, as indicated in the methods section, after certain slipping distance (usually between 5 cm to 10 cm), a true slip and fall phenomena was altered by the fall arresting rig. Thus predicting falls utilizing slip distance classification (beyond slip distance of 5 cm to 10 cm) may give erroneous fall predictions. In this experiment slip distances were categorized into time dependent measures utilizing actual kinematics as well as the kinetic profiles. Using these profiles together with the specified time domain (utilizing acceleration profile of the heel), accurate assessment of slip distances and falls were predicted in robust manner (Table 3) (for example slipping over 3.91 cm for younger

individuals in SDI time domain resulted in falls). In addition, as indicated by the Slip Recovery Threshold, classifying slip distance and predicting falls using the same standard for the entire population maybe inaccurate due to the fact that the different age groups exhibited different threshold values and characteristics of slips.

Previous studies relating the sliding heel velocity and fall events indicated that if the heel slipped in excess of 50 cm/sec (peak sliding heel velocity), falls resulted (Strandberg and Lanshammar, 1981). However, in this study, younger individuals on the average slipped faster than 140 cm/sec (average sliding heel velocity) and made complete recoveries from slipping without falling. Thus previous input range of SHV in dynamic COF measurement devices to 0 cm/sec to 100 cm/sec (Grönqvist, 1995) may be too conservative (e.g., 40 cm/sec \pm 2 cm/sec, Grönqvist et al., 1989). In addition, the profiles of the heel velocity and sliding heel velocity (Figure 5) suggest that, utilizing the peak SHV for input ranges for the dynamic COF measurement device may not be robust due to the fluctuations associated with Peak SHV. However, taking time dependent measures of SHV (average sliding heel velocity during slipping time) can assess the input slip parameters in a more robust and accurate manner.

Although the implications regarding standard COF measurements were made in this study, the floor surface used in this experiment (oily vinyl) most likely influenced many of the slip parameters. For example, Morach (1993) found that peak SHV may be as high as 275 cm/sec, whereas Strandberg and Lanshammar (1981) listed the critical speed as 50 cm/sec. Grönqvist, 1995, suggested that on Morach's (1993) study, trials usually (90%) resulted in a fall, whereas only 19% of the experiments by Strandberg and Lanshammar (1981) were falls. Thus it seems that the different environment (slipperiness) produces different dynamic characteristics of slips and falls. In this study, falls occurred in about 30% of the total trials utilizing an oily vinyl floor surface. Thus, caution should be made when deciding on standard COF values as well as for devices used to obtain COF measures.

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- Winter, D. A., Patla, A. E., Frank, J. S., and Walt, S. E., 1990, Biomechanical walking pattern changes in the fit and healthy elderly. *Phys. Ther.* 70: 340-347.



Memorandum

Date: May 2, 2001

From: Roy M. Fleming, Sc.D., Director, Research Grants Program RMF
Office of Extramural Programs, NIOSH, D30

Subject: Final Report Submitted for Entry into NTIS for Grant 1 R03 OH003917-01.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment

cc: Sherri Diana, EID, P03/C13

List of Publications

20026161 Lockhardt TE, Smith JL, Woldstad JC, Li P: Effects of Musculoskeletal and Sensory Degradation Due to Aging on the Biomechanics of Slips and Falls. Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA pp. 5-83 - 5-86, 2000

20026160 Lockhardt TE, Woldstad JC, Smith JL, Hsiang S, Li P: Prediction of Falls Using a Robust Definition of Slip Distance and Adjusted Required Coefficient of Friction, Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA. pp. 4-506 - 4-509, 2000

NIOSH Extramural Award Final Report Summary

Title: Effects of Musculoskeletal and Sensory Degradation Due to Aging on the Biomechanics of Slips and Falls
Investigator: Jeffrey C. Woldstad, Ph.D.
Affiliation: Texas Tech University
City & State: Lubbock, TX
Telephone: (806) 742-3543
Award Number: 1 R03 OH003917-01
Start & End Date: 9/30/1999–9/29/2000
Total Project Cost: \$36,500
Program Area: Not NORA
Key Words:

Abstract:

The proposal called for a one-year study to investigate the process of initiation and recovery of inadvertent slips and falls. The specific aim of the proposed research was to investigate the changes in the biomechanical parameters of walking and ground reaction forces due to intrinsic deficits associated with increase in age. More specifically, how deterioration of muscular strength and sensory degradation among older individuals affect biomechanical parameters of slip and fall accidents under normal and abnormal conditions.

The investigation compared biomechanical parameters of walking in three age groups; (18-30 years), (35-59 years), and 65 years or over). Biomechanical parameters included; stride length, heel velocity, required coefficient of friction, slip distance, and position and velocity of center of gravity of the whole body during heel contact phase of the gait. These parameters were measured utilizing force platforms, a 3-D motion analysis system, and a fall arresting rig. To determine the position and velocity of center of gravity during heel contact phase of the gait, a 3-D link segment model was utilized. Walking surfaces included oily vinyl tiles (dynamic coefficient of friction (DCOF) = 0.08) and outdoor carpet (DCOF = 1.80). Subjects walked according to their natural cadences. A sensory organization test was also performed to obtain information concerning the subject's proprioceptive, visual and vestibular systems. These sensory components were measured using an Equitest Posturography Platform. In addition, isometric strength test was performed (using a force transducer) to obtain information concerning the subject's over all strength.

The results indicated that younger subjects slipped as often as the elderly subject; however, the recovery process of older individuals was much slower and less effective. The ability to successfully recover from a slip (thus preventing a fall) is believed to be affected by lower extremity muscle strength and sensory degradation in elderly individuals.

Publications

Lockhardt TE, Smith JL, Woldstad JC, Li P: Effects of Musculoskeletal and Sensory Degradation Due to Aging on the Biomechanics of Slips and Falls. Proceedings of the IEA 2000/HFES 2000 Congress, July 2000, San Diego, CA pp. 5-83 - 5-86, 2000

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