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

Thurmon E. Lockhart[a], James L. Smith[a], Jeffrey C. Woldstad[b], and Pingshan Li[a]
[a]Department of Industrial Engineering, Texas Tech University, Lubbock, TX
[b] Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR

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

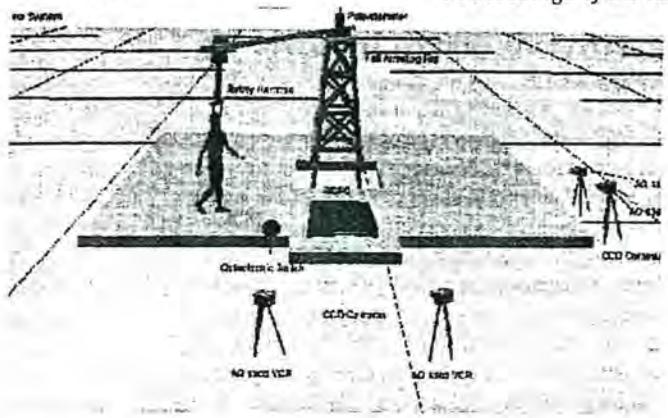

Figure 1. Field layout of the experiment.

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 x 2 x 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 x 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.

<u>*Calculations of dependent measures*</u>; 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 ($F(2,39) = 6.676$, $p \approx 0.003$, $\varepsilon = 1.053$). 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 ($F(2,39) = 4.817$, $p \approx 0.067$, $\varepsilon = 1.053$).

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 ($F(2,39) = 2.392$, $p \approx 0.105$, $\varepsilon = 1.053$).

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 (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). 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 ($F(2,39) = 13.434$, $p \approx 0.0001$, $\varepsilon = 1.053$).

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

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

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

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

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.

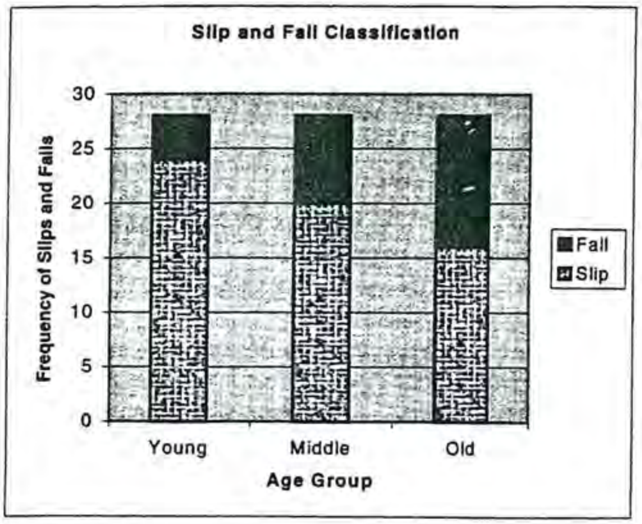

Figure 2. Slip and fall classification by the age group.

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 research on slips and falls concentrates predominantly on initiation of slips (i.e. RCOF), however, this study indicates that how slips result in a fall is important as well. Therefore, future research should focus not only on the dynamics of slips, but the dynamics of falls.

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Human Factors and Ergonomics Society
P.O. Box 1369
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