Proceedings of the Human Factors and Ergonomics Society Annual Meeting

http://pro.sagepub.com/

Relationship between Transitional Acceleration of the Whole Body Center-Of-Mass and Friction Demand Characteristic during Gait

Thurmon E. Lockhart, Jeffrey C. Woldstad and James L. Smith

Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2002 46: 1186

DOI: 10.1177/154193120204601338

Relationship Between Transitional Acceleration of the Whole Body Center-of-Mass and Friction Demand Characteristic During Gait.

Thurmon E. Lockhart[a], Jeffrey C. Woldstad[b], and James L. Smith[c]
[a]Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA
[b] Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR
[c]Department of Industrial Engineering, Texas Tech University, Lubbock, TX

A laboratory study was conducted to examine the gait changes associated with aging and the effect of these changes on initiation of slips, initial friction demand, and slip distance utilizing newly defined biomechanical parameters of slips and falls. Twenty-eight subjects from two age groups (young and old) walked around a circular track at a comfortable pace wearing a safety harness. Slippery floor surface was automatically placed on the walking track over force platforms at "unexpected" random time intervals utilizing remote controlled floor changer. Synchronized kinetic and kinematic measures were obtained on both slippery and non-slippery floor surfaces. The results indicated that older subjects step length was significantly shorter, and transitional acceleration of the whole body center-of-mass (COM) was significantly slower than their younger counterparts. Older subjects initial friction demand as measured by required coefficient friction (RCOF) was not significantly different than their younger counterparts. Additionally, older subjects slipped longer and faster than younger subjects. Bivariate correlation analyses suggested that transitional acceleration of the whole body COM was significantly related to friction demand characteristic (e.g., RCOF). These findings suggest that gait changes associated with aging (especially slower transition of the whole body COM) may affect initiation of slip-induced falls among older adults.

INTRODUCTION

Injuries associated with fall accidents pose a significant problem to society, both in terms of human suffering and economic losses. Older adults are particularly at risk. Falls are the leading cause of death resulting from injury among older adults (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). Fall-related injuries can be costly, approximately 95% of hip fractures result from falls (Nyberg, Gustafson, et al., 1996), and the estimated total annual cost of hip fracture in the US could reach $82- $240 billion by the year 2040 (Schneider and Guralnick, 1990). Furthermore, with longer life expectancy and the proportion of the elderly in the overall population (Manton et al., 1991), increasing numbers of slip and fall injuries can be expected.

Falling is often initiated by slips (Cham and Redfern, 2001). Most slips that lead to falls occur when the frictional force (F_μ) opposing the movement of the foot is less than the horizontal shear force (F_h) at the foot during the heel contact phase of the gait cycle (Perkins and Wilson, 1983). 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, and calculated the ratio of horizontal to vertical foot forces (F_h/F_v). This ratio (F_h/F_v) has been used to identify where in the gait cycle a slip is most likely to occur (slip initiation). Analyzing this ratio, Perkins suggested that dangerous forward slips were most likely to occur shortly after (< 50-100 ms) the heel contact phase of the gait cycle (peak 3). Currently this ratio (F_h/F_v at peak 3) is termed "Required Coefficient of Friction (RCOF)" (Redfern and Andres, 1984). Hanson, Redfern, and Mazumdar (1999) have reported the number of slip and fall events increased as the difference between the RCOF and measured dynamic COF of the floor surface increased.

Characteristics associated with transition of the whole body center-of-mass (COM) may play an important role in variation of horizontal as well as vertical foot force components during and after heel contact and, may influence likelihood of slip induced falls. In normal level walking, the whole body COM describes a smooth sinusoidal curve when projected on the plane of progression. The summits occur at the middle of the stance phase of each side and the lowest point occurs during double support when both feet are on the ground. At the time of the heel contact, the whole body COM is falling and progressing forward. As a result, RCOF (i.e., friction demand) may be altered. Recently, Pai and Patton (1997); and You, Chiou and Su (2001) have reported that the whole body COM velocity was an important factor in predicting balance conditions of the subjects. Additionally, Lockhart et al., (2000) found that older individuals whole body COM velocity during the heel contact phase of the gait cycle was slower than their younger counterparts. Consequently, older subjects exhibited slower transition of the whole body COM (i.e., transitional acceleration of the whole body COM between heel contact to shortly after heel contact). This slower transitional acceleration of the whole body COM of the older adults may influence slip initiation due to alteration of the ground reaction forces, and may affect likelihood of slips and falls.

Although much has been learned over the last few decades about age-related gait and postural adaptations, still little is known about the relationship between these changes and mechanisms involved in slip-induced falls. It was hypothesized that gait and postural changes among older adults, specifically slower transitional acceleration of the whole body COM, would affect severity of slip initiations and ultimately result in more falls than their younger counterparts.

METHOD

Subjects. Fourteen young 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.)	Old (65 yrs. and over) Mean (S.D.)
Age (yr)	22.6 (2.1)	75.55 (6.76)
Ht (cm)	169.7 (6.1)	170.2 (6.4)
Wt (kg)	68.7 (9.6)	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. Prior to participating in the experiment, older subjects were examined by a physician to ensure that they were in generally good physical health. Subjects also received a peripheral neuropathy examination in the Neurology Department at St. Mary's Hospital in Lubbock, Texas. Subjects were excluded from the study based on these tests (below 50% of the norm), and the physician's professional judgment. Each participant completed an informed consent procedure approved by the Texas Tech Institutional Review Board. 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 rectangular track using an overhead fall arresting rig. 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. 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 sampled at a rate of 180 Hz.

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) – results not reported here. Afterwards, the NeuroCom Sensory Organization Test was performed to measure sensory function and balance – results not reported here. During the experiment, the subjects walked across each floor condition for 10 min with and without the load (total of 20 minutes) – load condition not reported here. 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. 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.

For each step, step length (SL), step length index (SLI – normalized step length according to stature), RCOF, $\dot{v}_{COM}$ (transitional acceleration of the whole body COM), v_{COM} (Velocity of the whole body COM), slip distance (SD) were calculated as described by Lockhart et al., (2000b). SL, SLI, RCOF, $\dot{v}_{COM}$, v_{COM}, and SD were analyzed using one-way repeated measures ANOVA with age groups as the independent variable ($\alpha = 0.05$). Bivariate correlation analyses were performed on RCOF and $\dot{v}_{COM}$, and RCOF and v_{COM}. A computer algorithm was written (C++) to objectively determine the dependent measures.

RESULTS

To conserve space, only effects related to the age variable will be presented.

Consistent with previous findings (Winter, 1991; Lockhart, 1997), a reduction in step length was observed for the older individuals. In general, the result of one-way ANOVA indicated statistically significant ($p \leq 0.05$) SL differences between the age groups ($F_{(1,26)} = 5.307, p \approx 0.029$). Similarly, the ANOVA analysis of SLI also showed significant effects for the age groups ($F_{(1,26)} = 8.605, p \approx 0.007$). Additionally, v_{COM} was significantly slower than their younger counterparts ($F_{(1,26)} = 3.334, p \approx 0.046$), and older adults transitional acceleration of the whole body COM ($\dot{v}_{COM}$) was significantly slower than their younger counterparts ($F_{(1,26)} = 4.329, p \approx 0.0201$). Although the mean RCOF for older adults was higher than their younger counterparts, the one-way ANOVA analysis of RCOF indicated no statistically significant difference between the age groups ($F_{(1,26)} = 1.763, p < 0.1958$). Additionally, older adults SD was significantly longer than their younger counterparts ($F_{(1,26)} = 4.075, p < 0.05$). Table 2 summarizes the mean values and standard deviations for each of the dependent measures as a function of age.

Furthermore, the relationships between gait parameters (v_{COM} and $\dot{v}_{COM}$) and initial friction demand (e.g., RCOF) was quantified to assess relationships between the whole body COM and its influence on initial friction demand characteristic (i.e., slip severity). Relationship between RCOF and progression of the whole body COM (v_{COM}) [Figure 1], and transitional acceleration of the whole body COM ($\dot{v}_{COM}$) (Figure 2) was significant.

Table 1. Summary of the gait parameters.

		Young	Old
Variables	***Symbol***	Mean (S.D.)	Mean (S.D.)
Step Length (cm)	**SL**	65.35 (7.45)	58.97 (7.93)
SL Index (SLI)	**SLI**	.39 (0.04)	.35 (0.03)
*Whole body COM Velocity (cm/s)	v_{COM}	120.81 (14.19)	107.69 (16.41)
*Transitional Acceleration of COM (cm/s^2)	$\dot{v}_{COM}$	303.93 (11.85)	200.30 (5.18)
* Initial Friction Demand	**RCOF**	.177 (0.02)	.187 (0.02)
** Slip Distance (cm)	**SD**	4.98 (4.8)	7.65 (4.9)

* Measured on carpeted floor surface only.

** Measured on oily vinyl floor surface only.

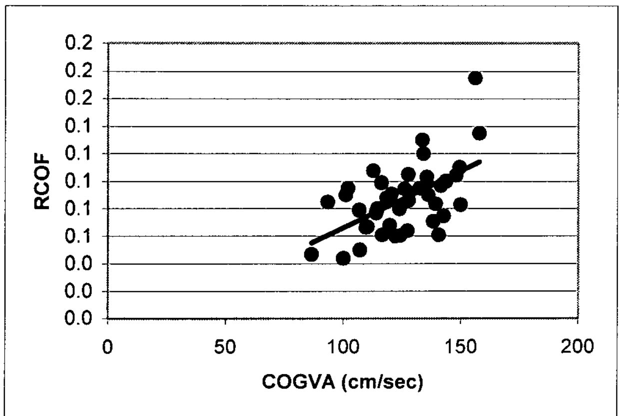

Figure 1. Correlation between RCOF and progression of whole body COM. R^2 =.48 suggest that RCOF is a function of walking velocity (or progression of whole body COM).

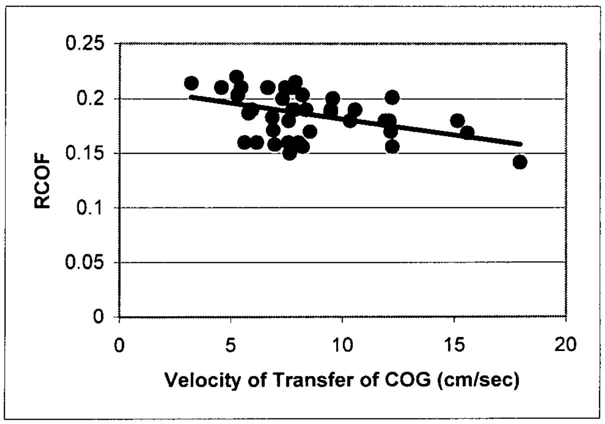

Figure 2. Correlation between RCOF and transitional acceleration of the whole body COM ($\dot{v}_{COM}$), R^2=.23.

DISCUSSION

The purpose of this study was to investigate mechanisms associated with slip and fall accidents among older adults. Specifically, this study analyzed factors influencing the initiation phase of slip-induced falls utilizing friction demand characteristics of young and older adults, and effects of transitional acceleration of the whole body COM on RCOF.

Although several investigators suggested initial gait characteristics such as step length and walking velocity may affect RCOF due to the increase in horizontal foot force, current study suggest that factors influencing transitional acceleration of the whole body COM may also influence slip initiation (i.e., friction demand). In order to elaborate on this statement, stick figures (of a subject during a typical slip-grip response with progression of the whole body COM and vertically projected angle θ between the instance of the heel contact [θ1], and shortly after the heel contact [θ2]) are illustrated in Figure 3. As the transfer of the whole body COM progresses forward, projected angle θ decreases from heel contact to shortly after heel contact. At the time of the heel contact (θ1), force vectors applied by the contacting foot (especially the horizontal foot force) will be greater than the horizontal force vector applied after heel contact (θ2) as a result of force-angle relationship. In other words, friction demand decreases from θ1 to θ2. Additionally, quicker transition of the whole body COM may be beneficial in terms of reducing friction demand and associated reduced likelihood of slipping. Thus, slower transfer of the whole body COM among older adults may increase friction demand at shoe/floor interface even though older adults step length was shorter and walking velocity was slower than their younger counterparts.

Although implicated, recent findings (Khuvasanont and Lockhart, 2002; Kim and Lockhart, 2002) along with current study suggest that friction demand characteristics among young and older adults are not statistically significant, thus, conclusion that higher RCOF is a function of age is premature. Further study investigating mechanisms involved in higher RCOF (e.g., higher horizontal heel contact velocity, slower hamstring muscle activation rate during heel contact phase, and lower power generation of the push-off foot among older adults, etc.) is needed to elucidate this possibility. Additionally, lack of significant RCOF differences between young and older adults and significant slip distance differences between young and older adults suggest that factors influencing recovery of slips should be explained further to understand intricate mechanisms associated with slip and fall accidents among older adults.

Acknowledgements

This research was supported by the National Institute of Health (NIOSH) grant R03/small grant. The paper's contents are solely the responsibility of the authors and not necessarily represent the official views of the NIH.

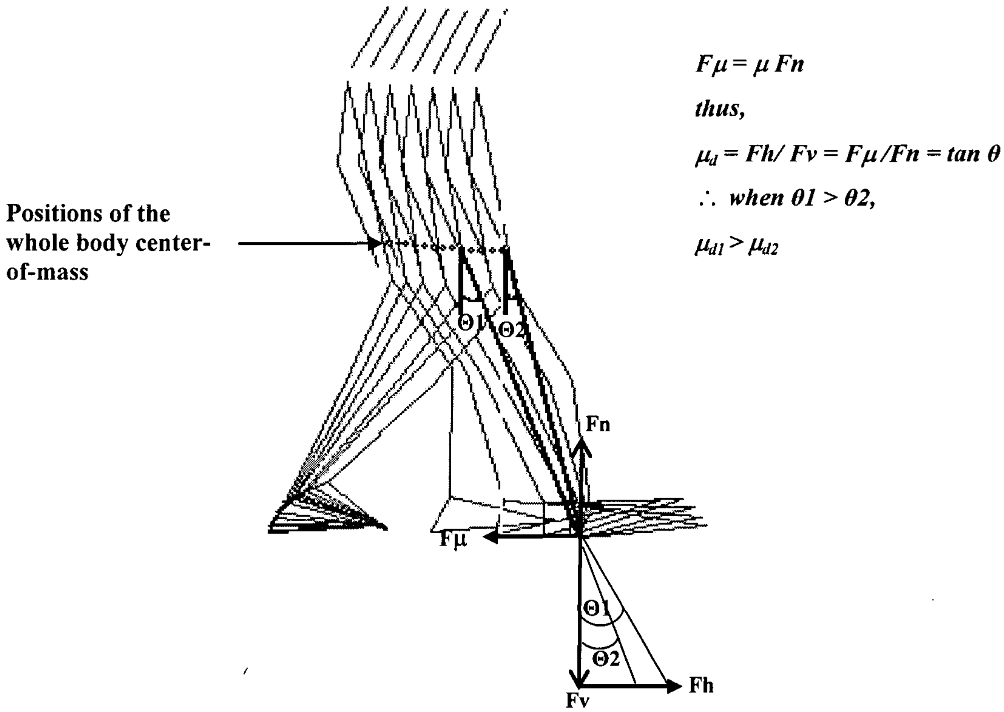

Figure 3. Positions of the whole body COM and force vectors applied by the left foot during heel contact phase in normal level walking, where, θ1 and θ2 = vertically projected angles associated with position of the whole body COM after heel contact and before heel contact respectively; Fh = horizontal; Fv = vertical; Fμ = frictional; and Fn = normal forces; μ = coefficient of friction; μ_d = friction demand; μ_{d1} = friction demand at heel contact associated with θ1; and μ_{d2} = friction demand after heel contact associated with θ2.

References

Campbell, A.J., Reinken, J., Allan, B.C., & Martinez, G.S., 1981, Falls in old age; a study of frequency and related factors. *Age Ageing* , 10, 264-270.

Center for Disease Control (2000): Falls and hip fractures among older adults. [Webpage]. Retrived August 14, 2001 from the world wide web: http://www.cdc.gov/ncipc/factsheets/falls.htm.

Cham, R., and Redfern, M.S., 2001, Load carrying and corrective responses to slip events. *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*, 962-966.

Cook, A.S., Baldwin, M., Yak, N., Pollissar, L., and Gruber, W., 1997, Predicting the probability for falls in community dwelling older adults. *Physical Therapy*, 77 (8), 812-819.

Cummings, S.R., Rubin, S.M., and Black, D., 1990, The future of hip fractures in the United States. *Clinical Orthopaedics and Related Research*, 252: 163-166.

Exton-Smith, A.N., 1977, Functional consequences of aging: Clinical manifestation, in Exton-Smith A.N., Grimeley-Evans J (eds): *Care of the Elderly: Meeting the challenge of dependency*. London: Academic Press, 41.

Koch, M, Schalk, M.G., Baker, D., Palumbo, S., and Tinetti, M., 1994, An impairment and disability assessment and treatment protocol for community living elderly persons. *Physical Therapy*, 74(4), 286-298.

Khuvasanont, T., and Lockhart, T.E., (2002), Age-related ankle strength and the effects on the slip-induced falls. *The Proceeding of the XVI Annual International Society of Occupational Ergonomics and Safety (ISOES),* Toronto, Canada, June, 9, 2002. Slips, Trips & Falls III. Session 5-4, pp 1-5.

Kim, S., and Lockhart, T.E., (2002), Effects of age-related changes in hamstring activation rate and heel contact velocity on the biomechanics of slips and falls. *The Proceeding of the XVI Annual International Society of Occupational Ergonomics and Safety (ISOES),* Toronto, Canada, June, 9, 2002. Slips, Trips & Falls III. Session 5-2, pp 1-5.

Leamon, T.B. and Murphy, P.L., 1995, Occupational slips and falls: more than a trivial problem. *Ergonomics*, 38:3, 487-498.

Lockhart, T.E. 1997, The ability of elderly people to traverse slippery walking surfaces. *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*. 1: 125-129.

Lockhart, T.E., Smith, J.L., Woldstad, J.C., and Lee, P.S., 2000a, Effects of Musculoskeletal and Sensory Degradation due to Aging on the Biomechanics of Slips and Falls. *Proceedings of the IEA/HFES Conference, 2000*. 5: 83-86.

Lockhart, T.E., Smith, J.L., Woldstad, J.C., and Hsiang, M., 2000b, Prediction of Falls Using a Robust Definition of Slip Distance and Adjusted Required Coefficient of Friction. *Proceedings of the IEA/HFES Conference, 2000*. 4: 506-509.

MacKinnon, C.D. and Winter, D.A., 1993, Control of whole body balance and posture in the frontal plane during human walking. *J. Biomechanics*, 26(6), 633-644.

Manton, K. G., Stallard, E. and Singor, B. H., 1991, *Future Demographic Trend in Europe and North America. What Can We Assume Today?* London: Academic Press.

National Safety Council, 1998, *Accidents Facts 1998 edition.* Itasca, IL.: Author.

Nyberg, L., Gustaftson, Y, Berggren, D., Brannstrom, B. and Bucht, G., 1996, *Falls leading to femoral neck fractures in lucid older people.* J Am Geriatr Soc. 44:156-160.

Perkins, P.J., and Wilson, M.P. (1983) Slip resistance testing of shoes - New developments. *Ergonomics*, 26(1): 73-82.

Redfern, M.S. and Andres, R.O. 1984, The analysis of dynamic pushing and pulling; required coefficients of friction, *in Proceedings of the 1984 International Conference on Occupational Ergonomics*, Toronto, 569-572.

Sattin, R.W., 1992, falls among older persons: A public health perspective. *Ann. Rev. Pub. Health*, 13: 489-508.

Schneider, E. L. and Guralnick, J. M., 1990, The aging of America: impact on hearlth care costs. *JAMA*; 263:2335-40.

Winer, B. J., Brown, D. R., and Michels, K. M., 1991, statistical Principles in Experimental Design (3rd. ed.). New York, NY: McGraw-Hill.

Winter, D.A. 1991, The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological. 2nd Edit. University of Waterloo Press, Waterloo, Canada pp. 87-94.