

Relationship between age-related gait adaptations and required coefficient of friction

Sukwon Kim ^a, Thurmon Lockhart ^{a,*}, Hoon-Yong Yoon ^b

^a *Industrial and Systems Engineering, Virginia Polytechnic and State University,
Blacksburg, VA 24061, USA*

^b *Industrial and Systems Engineering, Dong-A University, Pusan, South Korea*

Abstract

A laboratory study was conducted to evaluate if age-related gait adaptations in walking velocity, step length and heel contact velocity could adversely influence friction demand characteristics (i.e. RCOF) and the likelihood of slip initiation. Additionally, relationship between transitional acceleration of the whole body center-of-mass (COM) and friction demand was assessed between young and older participants. Fourteen younger (7 females and 7 males, 18–30 years old) and 14 older (7 females and 7 males, over 65 years old) adults participated in the study. While wearing a safety harness, all participants walked at their preferred gait speed for approximately 20 min on the linear walking track, and synchronized ground reaction forces and posture data were captured using the force plates and six infrared cameras, respectively.

The results indicated that older adults walked slower with slower heel contact velocity, and produced lower friction demand (i.e. RCOF) in comparison to younger adults. However, ANCOVA indicated that the differences in heel contact velocity between the two age groups were due to effects of walking velocity. The multiple regression and bivariate regression analyses suggested that, for older adults, heel contact velocity was a predictor for the RCOF, whereas, for younger adults, walking velocity, step length and transitional acceleration of the whole body COM were the factors contributing to the RCOF.

* Corresponding author. Tel.: +1 540 231 9088; fax: +1 540 231 3322.
E-mail address: lockhart@vt.edu (T. Lockhart).

In conclusion, the present study suggested that gait adaptations among the elderly must be considered when predicting the likelihood of slip initiation.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Walking velocity; Age; Friction demand; Gait; Slip initiation

1. Introduction

With longer life expectancy and the proportion of the aged individuals in the overall population increasing, numbers of slip and fall injuries over the age of 65 are expected to increase (Popovic, 2001; Brainsky et al., 1997). The National Safety Council reported that in 2001 (National Safety Council, 2005), the number of deaths caused or led by falls was 15,400 in US and 80% of those were over the age of 65 (Center for Disease Control and Prevention, 2003). The outcome of fall-related injuries among older adults resulted in hospitalization five times more often in comparison to injuries from other causes (Alexander et al., 1992). Center for Disease Control and Prevention (2003) reported that, in 2001, emergency departments treated more than 1.6 million seniors due to fall-related injuries and 373,000 were admitted to hospital. More than \$20 billion is estimated for fall-related medical expenses each year in US (National Safety Council, 2005). By 2020, the cost of fall injuries is expected to reach \$43.8 billion (Englander et al., 1996). To minimize these personal and economic losses, various age-related factors associated with prevention of slip and fall accidents must be explored and understood, especially for high-risk individuals such as older adults over the age of 65. Furthermore, it is essential to study contributing factors for slip-induced falls among the elderly during ambulation since slip initiating events/environment has been suggested as a source of large percentage of the total fall-related accidents among the elderly. As such, this study was designed to assist development of necessary prediction tools utilizing age-related gait parameters to prevent slip-induced falls.

Increasing age can have an effect on gait due to postural and balance changes. In general, older adults tend walk slower with higher heel contact velocity and a shorter step length. These age-related gait adaptations have been suggested to influence the likelihood of slip-induced falls (Ostrosky et al., 1994; Prince et al., 1997; Lockhart et al., 2003).

In terms of slip-induced falls, friction demand characteristics between the shoe-sole surface and the floor surface has been implicated as important predictor variable related to severity of falls. Dangerous forward slips that lead to falls are most likely to occur 70–120 ms after the heel contacts the ground (Gronqvist, 1995; Perkins, 1978). This is characterized by the ratio between horizontal ground reaction force (F_h) and vertical ground reaction force (F_v) and was referred to as “required coefficient of friction (RCOF)” (Redfern and Andres, 1984). The RCOF or friction demand represents the minimum coefficient of friction that must be available at the shoe–floor interface to prevent slip initiation (i.e. friction demand). The number of slip and fall events increased as the difference between the RCOF and measured

dynamic COF of the floor surface increased (Hanson et al., 1999). Most slips that led to falls occurred when the frictional force (F_{μ}) opposing the movement of the foot was less than the horizontal shear force (F_h) at the foot during the heel contact phase of the gait cycle (Irvine, 1986; Perkins and Wilson, 1983).

Several gait parameters associated with age-related gait adaptations are noted for influencing friction demand characteristics. For example, walking speed directly affects the magnitude of shear force (F_h), and therefore also has a direct effect on the friction demand (RCOF) during locomotion. In terms of kinematics (i.e., step length), 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). Furthermore, higher heel contact velocity was thought to increase horizontal shear force at the time of heel contact (Perkins and Wilson, 1983). Higher heel contact velocity among older adults was reported in comparison to younger adults (Mills and Barrett, 2001; Winter, 1991), and an increase in heel contact velocity was considered to increase the likelihood of slip-induced falls (Irvine, 1986; Karst et al., 1999; Mills and Barrett, 2001).

Studies (Lockhart et al., 2003; Pai and Patton, 1997) also suggest that the whole body center of mass (COM) velocity relative to the base of support among older adults may be a determining factor that was related to RCOF. Slower whole body COM velocity as well as slower whole body COM transitional acceleration (velocity changes from heel contact to shortly after heel contact) among older adults in comparison to younger adults were reported (Lockhart et al., 2003), and the slower whole body COM transfer was implicated as a contributing factor for slip-induced falls (Lockhart et al., 2003; Lockhart and Kim, in press; You et al., 2001).

Although much has been learned over the last few decades about fall accidents among the elderly, information regarding the relationships between age-related gait adaptations and friction demand characteristics is lacking (e.g., some of the above studies only examined younger individuals and most of the studies examined young and old individuals together—not differentiating the aging effects). As such, the primary goal of this study was to reevaluate if the hypothesized changes in step length, whole body COM velocity, transitional acceleration of the whole body COM, and heel contact velocity with advancing age would influence friction demand characteristics (i.e. RCOF). Understanding the relationship between the age-related gait parameters and friction demand characteristics can help identify slip prone individuals thereby reducing fall accidents.

2. Method

2.1. Participants

Fourteen young individuals (18–35 years old, 7 male and 7 female, 172.41 ± 10.93 cm, 71.59 ± 12.14 kg) and 14 older individuals (65 and older, 7 male and 7 female, 168.49 ± 9.09 cm, 72.58 ± 16.31 kg) participated in this experiment. The younger adults were recruited from the general student population at Virginia

Tech, Blacksburg, VA, and older adults were recruited from the local community, Blacksburg, VA. Each participant completed an informed consent procedure approved by the Virginia Tech Internal Review Board (IRB). No one had a neurological or muscular skeletal disorder that would complicate the study. A questionnaire was used as an initial screening tool.

2.2. Apparatus

Walking trials were conducted on a linear walking track (1.5 m × 20 m), which was elevated 15 cm above the floor surface (Fig. 1). The entire deck was covered with vinyl tile. The test surface was mounted on a platform and connected to force plates (BERTEC # K80102, TYPE 45550-08, Bertec Corporation, OH 43212, USA). All participants wore the same shoe (Athletic Works). A six-camera ProReflex system (Qualysis) was used to collect three-dimensional posture data of participants as they walked over the test floor surface. Kinematic data were sampled and recorded at 120 Hz. Ground reaction forces of participants walking over the test surfaces were measured using two force plates and sampled at a rate of 1200 Hz.

2.3. Procedure

A set of 24 markers were placed on participants' anthropometric landmarks (base of second toe, malleolus, epicondyle, greater trochanter, base of first phalanx of third finger, styloid process of ulna, lateral epicondyle of humerus, greater tubercle, acromion, and anterior portion of temporal bone). Also, two markers were placed on the

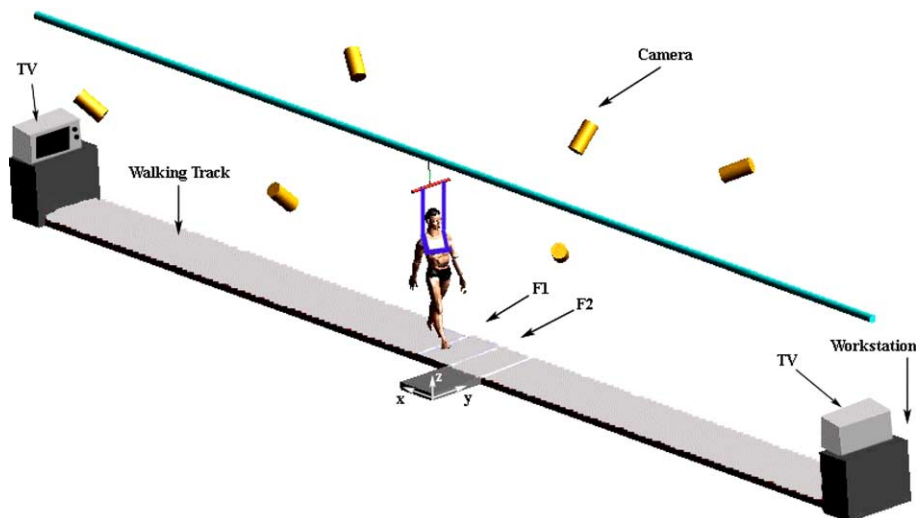


Fig. 1. Field layout of the experimental set-up including; fall arresting system, infrared cameras (6), two force plate (F1 and F2), and workstations. X, Y, and Z = global references for force and position.

heel (center of the calcaneus) to measure heel contact velocity. Participants walked across the vinyl floor surface for 20 min. They were instructed to walk straight and to look forward while walking at their preferred walking speed. Participants' cadence was measured within a subsequent 20 min session to ensure that their preferred walking speeds were consistent throughout the experiment. After ensuring that the preferred walking speeds were consistent (about 10–15 min into the session), participants' natural posture and ground reaction forces were collected for the analysis. Two trials were collected within the 20 min walking session (data from second trial was used only if first trial was not acceptable—i.e., stepping onto an edge of the force platform). They wore the same shoes to ensure that the RCOF was not influenced by shoe sole. It is important to note that this study was a part of a larger experiment involving slippery floor surfaces. The first session was associated with walking on dry floor surfaces only. Second session was associated with walking on dry and slippery floor surfaces after session one (at least two days separated the sessions). The data for this study was collected during the first session of the experiment.

2.4. Data analysis

The coordinate data from motion analysis system were used to calculate the gait parameters (the whole body COM velocity/transitional acceleration, and heel contact velocity). Ground reaction force data were used to determine RCOF and heel contact period. Ground reaction forces were measured using two force plates for 5 s at 1200 Hz, and were filtered using 4th order zero-lag lowpass-Butterworth-filter at cut-off of 6 Hz (Winter, 1991). Kinematic data were recorded for 5 s at 120 Hz, and were filtered using 4th order zero-lag lowpass-Butterworth-filter at cut-off of 12 Hz (Winter, 1991).

Descriptive and inferential statistical analyses were performed by utilizing the JMP statistical packages (SAS Institute Inc. Cary, NC, USA). The age group differences were evaluated using one-way analyses of variance (ANOVA) and analyses of covariance (ANCOVA) with the whole body COM velocity as a covariate to mitigate the effects of age-related walking velocity differences. Multiple regression analyses were performed to describe and predict the relationship between the independent (gait parameters) and dependent (RCOF) variables among young and old. The data was analyzed by utilizing techniques available for evaluating the assumptions of regression analysis. The predictor variables were selected by utilizing the cp and the backward elimination procedure for the dependent variable—RCOF. Several separate bivariate correlation analyses (3) were performed to quantify the relationship between effects of age, on the gait parameters of slip-induced falls (i.e., RCOF). The results were considered as statistically significant when $p \leq 0.05$.

2.5. Dependent variables

2.5.1. Heel contact velocity (HCV)

The instantaneous horizontal heel contact velocity (HCV) was calculated utilizing the heel position in horizontal direction at the foot displacement of 1/120 s before

and after the heel contact phase of the gait cycle. Heel contact was defined as the time when the vertical force (F_z) exceeded 7 N during the heel contact phase of gait cycle (Lockhart et al., 2003). Following heel contact, three continuous heel velocities excluding a heel velocity at heel contact were averaged to represent heel contact velocity.

2.5.2. The whole body COM velocity (also refer to as walking velocity—WV)

The whole body COM was calculated by averaging all of the centers of mass from the 14 segments as described by Lockhart et al. (2003) (left and right feet, left and right shanks, left and right thighs, trunk, left and right hands, left and right lower arms, left and right upper arms, head). The whole body COM velocities of the participants were calculated using the formula:

$$\text{COM velocity(WV)} = [X(i+1) - X(i-1)]/2\Delta t,$$

where X = position of COM

Ensemble average of the segmental whole body COM velocities during one step cycle was parameterized.

2.5.3. Step length (SL)

The linear distance was measured in the direction of progression between successive points of foot-to-floor contact of the first foot ($X1, Y1$) and other foot ($X2, Y2$). Step length was calculated from the distance between consecutive positions of the heel contacting the floor.

2.5.4. Transitional acceleration (TA) of the whole body COM

TA was defined as the relative horizontal whole body COM velocity differences over time between the whole body COM velocities 50 ms before heel contact and 50 ms after heel contact (Lockhart et al., 2003).

2.5.5. Required coefficient of friction (RCOF)

The required coefficient of friction was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force (F_x/F_z) after the heel contacted the vinyl floor surface (Fig. 2, peak 3 as defined by Perkins (1978)).

3. Results

3.1. Age group effect

Table 1 describes the summary of gait parameters (heel contact velocity, the whole body COM velocity, step length, and TA), and friction demand (RCOF) characteristics of young and old. The one-way ANOVA indicated that younger adults walked faster ($F_{1,27} = 8.56$, $p = 0.008$), and produced higher RCOF ($F_{1,27} = 11.08$, $p = 0.002$) than older adults. Also, younger adults' heel contact velocity was faster

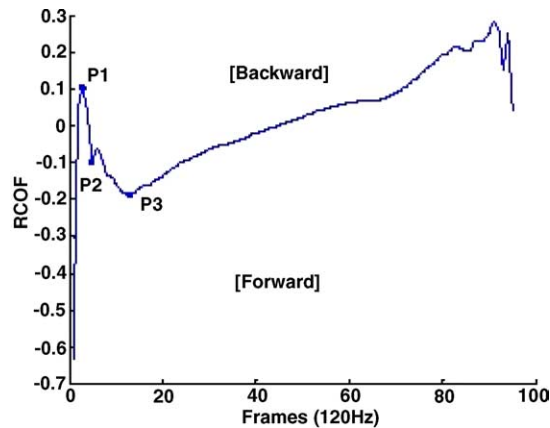


Fig. 2. Required coefficient of friction (RCOF) peaks during normal gait. Peak 3 is denoted by P3 and occurs shortly after heel contact.

Table 1

Summary of gait parameters (HCV—heel contact velocity, WV—walking velocity, SL—step length, RCOF—required coefficient of friction, TA—whole body COM transitional acceleration)

Variables	Young (18–35 year) Mean (SD)	Old (>65 year) Mean (SD)	ANOVA	ANCOVA
HCV (cm/s)	91.64 (30.36)	64.29 (24.78)	*	NS
WV (cm/s)	133.23 (11.59)	120.22 (10.12)	*	NT
SL (cm)	63.99 (6.39)	61.40 (6.76)	NS	NS
RCOF (F_x/F_z)	0.19 (0.02)	0.15 (0.02)	*	NT
TA (cm/s^2)	287.96 (122.11)	256.63 (81.51)	NS	

NS: not significant.

NT: not tested.

* $p < 0.05$.

than older adults' heel contact velocity ($F_{1,27} = 4.21$, $p = 0.05$). However, younger adults' step length ($F_{1,27} = 3.78$, $p = 0.07$) and TA ($F_{1,27} = 0.64$, $p = 0.43$) was not different from older adults.

The ANCOVA (Table 1) was used to evaluate if the results found in heel contact velocity was due to the effect of age not walking velocity. The ANCOVA suggested that higher heel contact velocity found among younger adults in comparison to older adults was probably due to the effects of walking velocity, not due to the effects of age.

3.2. Gait adaptation and the likelihood of slip initiation

To predict the RCOF for overall gait parameters, the multiple regressions were performed. Additionally, the bivariate regressions were performed to assess each gait parameter's effects on the RCOF among young and older adults.

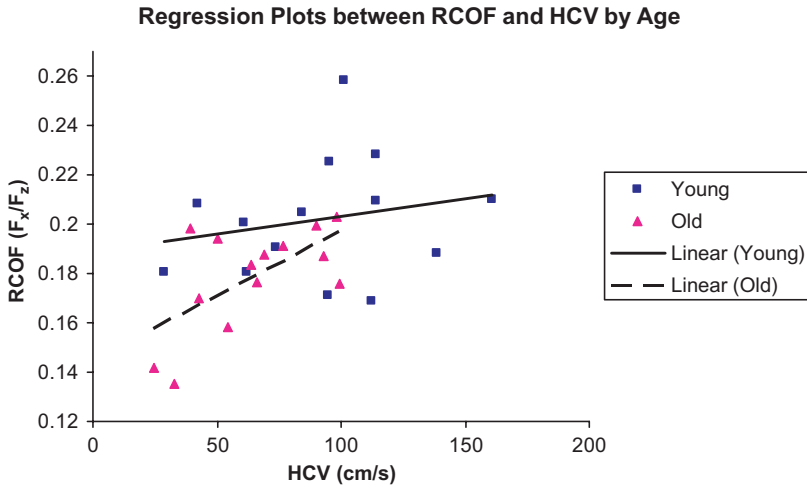


Fig. 3. Prediction of RCOF by HCV (cm/s) (Y: young, O: old).

The multiple regression analysis indicated that HCV and TA was factors which predicted the RCOF among older adults ($R^2 = 0.52$, $p = 0.02$, $\text{RCOF} = 0.1487004 + 0.0004801\text{HCV} + 0.0000634\text{TA}$), whereas, WV, TA, and SL were factors influencing the RCOF among younger adults ($R^2 = 0.58$, $p = 0.02$, $\text{RCOF} = 0.0480861 + 0.0006053\text{WV} - 0.000114\text{TA} + 0.0010859\text{SL}$).

The bivariate analyses among older adults also indicated that HCV ($F_{1,27} = 7.52$, $p = 0.01$, $R^2 = 0.38$) was correlated to RCOF, (Fig. 3). Additionally, SL ($F_{1,27} =$

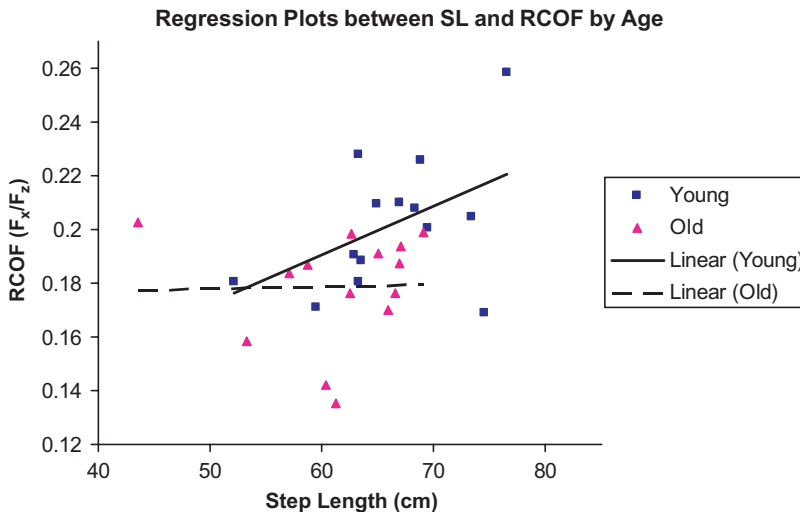


Fig. 4. Prediction of RCOF by step length (Y: young, O: old).

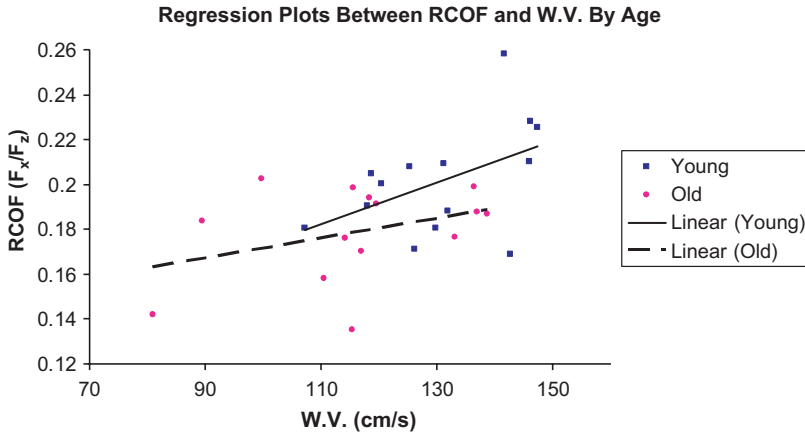


Fig. 5. Prediction of RCOF by WV (Y: young, O: old).

0.007, $p = 0.93$, $R^2 = 0$) (Fig. 4), WV ($F_{1,27} = 1.86$, $p = 0.19$, $R^2 = 0.13$) (Fig. 5), and TA ($F_{1,27} = 2.73$, $p = 0.12$, $R^2 = 0.18$) (Fig. 6) was not correlated to RCOF.

The bivariate analyses among younger adults suggested that HCV ($F_{1,27} = 0.70$, $p = 0.41$, $R^2 = 0.05$) was not correlated to RCOF (Fig. 3). In addition, SL ($F_{1,27} = 4.74$, $p = 0.05$, $R^2 = 0.28$) (Fig. 4), WV ($F_{1,27} = 4.44$, $p = 0.05$, $R^2 = 0.27$) (Fig. 5), and TA ($F_{1,27} = 8.08$, $p = 0.01$, $R^2 = 0.40$) (Fig. 6) were directly correlated to RCOF.

In essence, bivariate analyses for each group indicated that HCV was the better predictor of RCOF for old adults, whereas, WV, SL, and TA were better predictors of RCOF for young adults.

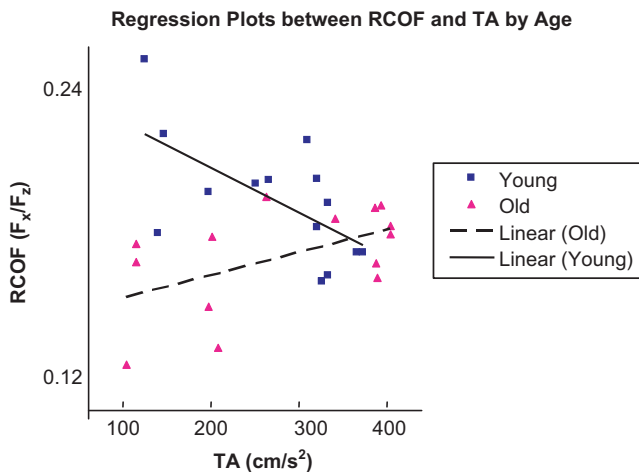


Fig. 6. Prediction of RCOF by TA (Y: young, O: old).

4. Discussion

The primary objective of the present study was to assess relationship between age-related gait adaptations and friction demand characteristics. Understanding the relationship between the age-related gait parameters and friction demand characteristics may help identify slip prone individuals thereby reducing fall accidents.

Previous literatures (Grönqvist et al., 1989; Karst et al., 1999; Lockhart et al., 2003; Myung et al., 1992; Lockhart and Kim, *in press*; Perkins, 1978) suggested that WV, HCV, TA, and SL were major predictors for the likelihood of slip-induced falls. However, information is lacking in terms of explaining age-related factors contributing to the likelihood of slip-induced falls. For example, previous studies characterizing age-related gait adaptations did not assess the friction demand characteristics (Karst et al., 1999; Lockhart et al., 2003; Myung et al., 1992; Lockhart and Kim, *in press*). Additionally, few studies (Carlsöö, 1962; Grönqvist et al., 1989) assessed the variations in the friction demand characteristics without including aging gait attributes.

In the present study, heel contact velocity was a predictor variable for the RCOF for older adults, whereas, for younger adults, walking velocity, transitional acceleration of COM, and step length were the predictors for RCOF. Lockhart and Kim (*in press*) suggested that heel velocity among younger adults was sufficiently reduced prior to heel contact due to proper activation of hamstring muscles, suggesting that HCV among younger adults was not a factor altering the RCOF. However, older adults may not be able to reduce their HCV due to degradations in hamstring muscles (Lockhart and Kim, *in press*). In the case of frail older individuals (with higher heel contact velocity), this information may be used to assess slip prone individuals by assessing their heel contact velocity. Although implicated, further studies investigating gait alterations of frail older adults are needed to elucidate this possibility.

Furthermore, WV, TA (Lockhart et al., 2003; Lockhart and Kim, *in press*) and SL (Grönqvist et al., 1989) have been identified to influence friction demand characteristics. Slower WV and shorter SL were suggested to decrease the RCOF due to its effects on alterations in horizontal as well as vertical ground reaction forces (Lockhart et al., 2003). In disagreements with the previous findings, older adults' RCOF was not predicted by WV, TA and SL, whereas, in agreement with previous findings younger adults' RCOF was predicted by WV, TA and SL. Walking capabilities among older adults are reduced due to degradations in neuromusculoskeletal system (Bendall et al., 1989; Delwaide, 1986; Prince et al., 1997; Trueblood and Rubenstein, 1991) as well as a fear of falling (Lesley et al., 2002) and, this is represented by slower walking velocity as well as shorter step length (Lesley et al., 2002; Lockhart et al., 2003; Ostrosky et al., 1994). Assuming that walking velocity as well as step length influenced friction demand characteristics in the present study, the RCOF could not be predicted by these parameters among older adults since older adults already attempted to reduce the chance of slipping by adapting to the safer gait strategy while younger adults did not. This effect may have been resulted due to the experimental protocols as well. As suggested previously, even though the walking protocol (dry vs. wet) was separated, subjects were aware of the slippery conditions by signing

the inform consent form. Thus, although suggested, further study utilizing only dry floor surfaces should be conducted to elucidate this possibility.

As implicated by Lockhart et al. (2003), the present study found that faster TA predicted lower RCOF for younger adults. Nonetheless, for older adults, faster TA predicted higher RCOF although it was not significant. These opposite results seen between two age groups may be influenced by the same mechanisms that explained sufficient HCV reductions seen in younger adults. We speculate that, in case of younger adults, the whole body COM slowed down sufficiently right before heel contact, and the whole body COM started accelerating sufficiently right after heel contact to maintain the forward body momentum. However, for the elderly, their gait adaptations which slowed down their gait speed may have minimized the effects of reducing the velocity of the whole body COM right before heel contact and influenced forward progression of the whole body COM after the heel contact phase of the gait cycle. This may be why there was opposite results between two age groups in predicting the RCOF with TA. It is also important to note that parameter differences between previous study (Lockhart et al., 2003) and current study. The previous study investigated gait parameter differences on slippery and non-slippery floor surfaces whereas the current study only concentrated on non-slippery floor surface. As such, the parameter results were somewhat attenuated for previous study compared to the current study.

In conclusion, the present study indicated that HCV was a predictor for older adults' friction demand characteristic, whereas, WV, TA, and SL were factors influencing younger adults' friction demand characteristic. Furthermore, these results may suggest that finding solutions to reduce HCV could be a prevention strategy in reducing slip-induced falls among frail older adults. Although implicated, effects of HCV and friction demand (and other gait variability/stability parameters) on slip-induced falls should be elucidated for optimal fall prevention strategy for frail elderly individuals.

References

- Alexander, B., Rivara, F., Wolf, M., 1992. The cost and frequency of hospitalization for fall-related injuries in older adults. *Am. J. Public Health* 82 (7), 1020.
- Bendall, M., Bassey, E., Pearson, M., 1989. Factors affecting walking speed of elderly people. *Age Ageing* 18, 327–332.
- Brainsky, G.A., Lydick, E., Epstein, R., Fox, K.M., Hawkes, W., Kashner, T.M., et al., 1997. The economic cost of hip fractures in community-dwelling older adults: a prospective study. *J. Am. Geriatr. Soc.* 45, 281–287.
- Carlsöö, S., 1962. A method for studying walking on different surfaces. *Ergonomics* 5, 271–274.
- Center for Disease Control and Prevention, 2003. Web-based Injury Statistics Query and Reporting System (WISQARS) [Online]. National Center for Injury Prevention and Control, Centers for Disease Control and Prevention (producer). Available from: <www.cdc.gov/ncipc/wisqars> (cited 24 November 2003).
- Delwaide, P., 1986. Disequilibrium and gait disorders in older people. *Rev. Clin. Gerontol.* 6, 41–48.
- Englander, F., Hodson, T.J., Terregrossa, R.A., 1996. Economic dimensions of slip and fall injuries. *J. Forensic Sci.* 41 (5), 733–736.

- Gronqvist, R., 1995. A dynamic method for assessing pedestrian slip resistance. Finnish Institute of Occupational Health, Helsinki, Research Report 2.
- Grönqvist, R., Roine, J., Jarvinen, E., Korhonen, E., 1989. An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions. *Ergonomics* 32 (8), 979–995.
- Hanson, J.P., Redfern, M.S., Mazumdar, M., 1999. Predicting slips and falls considering required and available friction. *Ergonomics* 42 (12), 1619–1633.
- Irvine, C.H., 1986. Evaluation of the effect of contact-time when measuring floor slip resistance. *J. Test Eval.* 1, 19–22.
- Karst, G.M., Hageman, P.A., Jones, T.V., Bunner, S.H., 1999. Reliability of foot trajectory measures within and between testing sessions. *J. Gerontol.* 54A, M343–M347.
- Lesley, B., William, G., Melody, P., Ryan, S., Toni, W., 2002. Central set influences on gait. *Exp. Brain Res.* 145, 286–296.
- Lockhart, T.E., Kim, S.W., in press. Relationship between Hamstring activation rate and heel contact velocity: factors influencing age-related slip-induced falls, *Gait & Posture*.
- Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of age-related gait changes on biomechanics of slips and falls. *Ergonomics* 46 (12), 1136–1160.
- Mills, P.M., Barrett, R.S., 2001. Swing phase mechanics of healthy young and elderly men. *Hum. Move. Sci.* 20, 427–446.
- Myung, R., Smith, J.L., Leamon, T.B., 1992. Slip distance for slip/fall studies. In: *Advances in Industrial Ergonomics and Safety IV. Proceedings of the Annual International Industrial Ergonomics and Safety Conference*. Denver, CO.
- National Safety Council, 2005. Protecting the elderly from the falls [Online]. Centers for Disease Control and Prevention (producer). Available from: <<http://www.nsc.org/news/bj032902.htm>> (cited 16 July 2005).
- Ostrosky, M., Jessie, M., Ray, G., Zena, G., Marty, E., 1994. A comparison of gait characteristics in young and old subjects. *Physical Therapy* 74 (7), 34–43.
- Pai, Y.C., Patton, J.L., 1997. Center of mass velocity-position predictions for balance control. *J. Biomech.* 30, 347–354.
- Perkins, P.J., 1978. Measurement of slip between the shoe and ground during walking. Special Technical Publication, 649. American Society of Testing and Materials, pp. 71–87.
- Perkins, P.J., Wilson, M.P., 1983. Slip resistance testing of shoes—New developments. *Ergonomics* 26 (1), 73–82.
- Popovic, J.R., 2001. National hospital discharge survey: annual summary with detailed diagnosis and procedure data. National Center for Health Statistics. *Vital Health Statistics* 13 (151), 154.
- Prince, F., Corriveau, H., Hebert, R., Winter, D.A., 1997. Gait in the elderly. *Gait Posture* 5, 128–135.
- Redfern, M.S., Andres, R., 1984. The analysis of dynamic pushing and pulling: required coefficients of friction. In: *Proceedings of the 1984 International Conference on Occupational Ergonomics*, Toronto, Ont., 1984.
- Trueblood, P.R., Rubenstein, L.Z., 1991. Assessment of instability and gait in elderly persons. *Comprehensive Ther.* 17, 20–29.
- Winter, D.A., 1991. *Biomechanics and Motor Control of Human Movement*, second ed. Wiley & Sons, Toronto, Ont.
- You, J.Y., Chou, Y., Lin, C.J., Su, F.C., 2001. Effect of slip on movement of body center of mass relative to base of support. *Clin. Biomech.* 16, 167–173.