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Comparisons of Spatial-Temporal Characteristics between Young and Old Adults While Walking: Factors Influencing the Likelihood of Slip-Initiation

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ABSTRACT

A laboratory study was conducted to evaluate if two different age groups(young vs. old) had differences in walking velocity and heel contact velocity and, furthermore, if these gait characteristics could adversely influence initial friction demand characteristics(i.e. RCOF) and the likelihood of slip-initiation. Twenty eight(14 younger and 14 older adults) participated in the study. While wearing a safety harness, all participants walked at their preferred gait speed for approximately 20 minutes on the linear walking track(1.5m×20m) consisting of two floor-mounted forced plates. During subsequent 20 minutes, synchronized ground reaction forces and posture data were captured using the two force plates and six infrared cameras, respectively. The results indicated that older adults walked slower(i.e., slower whole body center-of-mass velocity), exhibited lower heel contact velocity, and produced lower initial friction demand characteristics (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 the effects of walking velocity. The bivariate analysis further suggested that walking velocity was correlated to RCOF and heel contact velocity, while heel contact velocity was not found to be correlated to RCOF. In conclusion, younger adults' RCOF was higher than their older counterparts due to faster walking velocity. As such, walking velocity could be a better indicator for predicting initial friction demand characteristics(i.e. RCOF) not heel contact velocity.

Keyword: Walking velocity, Age, Friction demand, Gait

1. INTRODUCTION

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 F_h(horizontal component of the force exerted between the shoe and floor during normal walking) and F_v(vertical component of the force exerted between the shoe and floor during normal walking) 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. initial friction demand). The number of slip and fall events increased as the difference between the

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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 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. An increase in walking velocity and step length usually increases the friction demand (Carlsöö, 1962; James, 1983; Soames and Richardson, 1985; and Myung et al., 1992). 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).

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 1990), 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). Also, studies (Lockhart et al., 2003; Pai and Patton, 1997) suggested that the whole body center of mass (COM) velocity relative to the base of support among older adults might be a determining factor that was associated with RCOF. Slower whole body COM velocity as well as slower whole body COM transitional acceleration among older adults in comparison to younger adults were reported (Lockhart et al., 2003; Lockhart and Kim 2004 submitted; You et al., 2001), and the slower whole body COM transfer was implicated as a contributing factor for falls (Lockhart et al., 2003; Lockhart and Kim 2004 submitted; 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 (i.e. higher heel contact velocity and slower whole body COM velocity) and friction demand characteristics is lacking. The primary goal of the study was to evaluate if the hypothesized changes in walking velocity (i.e. whole body COM velocity) and heel contact velocity with advancing age will influence friction demand characteristics (i.e. RCOF). The present study was designed in order to provide appropriate information in regard to contributing factors for slip-induced falls among the elderly to assist developments of necessary prediction tools utilizing gait parameters to prevent slip-induced falls.

2. METHOD

2.1 Participants

Fourteen younger (18~35 years old, 7 male and 7 female) individual and 14 older (65 and older, 7 male and 7 female) individual 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. All participant read an inform consent form approved by the Virginia Tech Internal Review Board (IRB) and agreed to it. A questionnaire was used to screen out persons with history of joint injuries or neuromusculoskeletal disorders that would complicate the study.

2.2 Apparatus

Subjects walked on a 20m walking track (Figure 1). Two force plates (BERTEC # K80102, TYPE 45550-08, Bertec Corporation, OH 43212, USA) were mounted under the walking track. The entire walking track was covered with the same vinyl tile. A six-camera Pro-Reflex 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 120Hz. Ground reaction forces of participants walking over the test surfaces were measured using two force plates and sampled at a rate of 1200Hz. To synchronize kinematic and kinetic data in timely-manner, the Labview software was used to trigger Pro-Reflex system when data collection for force data was started.

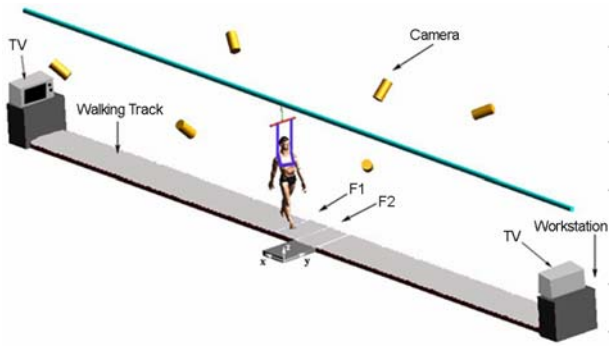

Figure 1. Field layout of the experimental set-up including; Fall Arresting System, Infra-red cameras (6), Two force plate (F1 and F2), and workstations. X,Y, and Z = global references for force and position.

2.3 Procedure

A set of 24 markers were placed on participants' anthropometric landmarks (base of second toe, malleolus, epicondyle, greater trochater, base of first phalange of third finger, styloid process of ulna, lateral epicondyle of humerus, greater tubercle, acromion, and anterior portion of temporal bone). Also, 2 markers were placed on the heel (center of the Calcaneus) to measure heel contact velocity. Participants walked across the vinyl floor surface for 20 minutes. 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 minute session to ensure that their preferred walking speeds were consistent throughout the experiment. After ensuring that the preferred walking speeds were consistent, participants' natural posture and ground reaction forces were collected.

2.4 Data analysis

Position data collected via ProReflex were used to calculate the gait characteristics (the whole body COM velocity, and heel contact velocity). Ground reaction forces (GRFs) were used to determine RCOF and heel contact time. A heel contact was defined where vertical GRF exceeded 7N. Ground reaction forces as well as position data were collected for 5 seconds at 1,200Hz and 120Hz, respectively. Lowpass-Butterworth-filters were used to remove noises at 6Hz for GRFs and at 12Hz for position data (Winter, 1991).

Descriptive and inferential statistical analyses were performed by utilizing the JMP statistical packages (SAS Institute Inc. Cary, NC, USA). The group differences in walking velocity were evaluated using one-way analyses of variance (ANOVA) and analyses of covariance (ANCOVA). In addition, correlations among walking velocity, heel contact velocity, and RCOF were evaluated using the bivariate correlation analysis. The results were considered as statistically significant when $p \leq 0.05$.

2.5 Dependent Variables

2.5.1 Heel contact velocity

The instantaneous horizontal heel contact velocity (HCV) was calculated utilizing the heel position in horizontal direction at the foot displacement of 1/120 second before and after the heel contact phase of the gait cycle. Heel contact was defined as the time when the vertical force (Fz) exceeded more than 7N during the heel contact phase of gait cycle.

2.5.2 Walking Velocity

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:

COM velocity = $[X(i+1) - X(i-1)] / 2\Delta t$, where X = COM

All of the whole body COM velocities during one step cycle were averaged; data were collected at 120Hz.

2.5.3 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 (Fx/Fz) after the heel contacted (peak 3 as defined by Perkins (1978)) the vinyl floor surface.

3. RESULTS

Table 1 described the summary of gait parameters (heel contact velocity and the whole body COM velocity), and friction demand (RCOF). The one-way ANOVA indicated that younger adults walked faster ($F_{1,26}$=8.56, p=0.008), and produced higher RCOF ($F_{1,26}$=11.08, p=0.002) than older adults. The one-way ANOVA indicated that younger adults' heel contact velocity was higher than older adults' heel contact velocity ($F_{1,26}$=4.21, p≒0.05). The ANCOVA indicated that younger adults' heel contact velocity was not different from older adults $F_{1,25}$ =0.08, p>0.78). The ANCOVA was used to evaluate if the results found in heel contact velocity was due to the effect of age not the whole body COM 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 the whole body COM velocity, not age.

The regression between two variables indicated significant direct correlations between RCOF and the whole body COM velocity ($F_{1,26}$=10.02, p=0.004, R^2=0.30) (Figure 2), and between the whole body COM velocity and heel contact velocity ($F_{1,26}$=39.35, p<0.0001, R^2= 0.54) (Figure 3), whereas, no significant correlation was found between RCOF and heel contact velocity ($F_{1,26}$= 0.91, p=0.34, R^2=0.03). The bivariate analyses suggested that an individual with faster velocity of the whole body COM required higher friction demand than an individual with slower whole body COM velocity.

Table 1. Summary of Gait Parameters

Variables	Young Mean (S.D.)	Older Mean (S.D.)	ANOVA	ANCOVA
HCV (cm/s)	74.36 (21.53)	57.06 (20.15)	*	N.S.
W.V. (cm/s)	130.23 (11.59)	118.22 (10.12)	*	N.T
RCOF (Fx/Fz)	0.187 (0.022)	0.153 (0.019)	*	N.T

*p<0.05,; N.S. (not significant); N.T. (not tested)

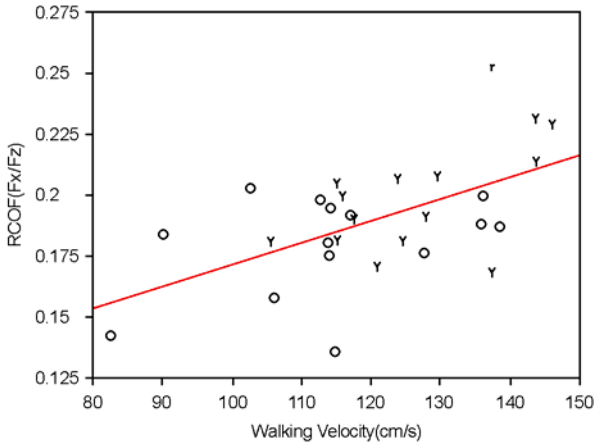

Figure 2. Bivariate Fit of RCOF (Fx/Fz) By Walking Velocity (cm/s) (Y: young, O: old)

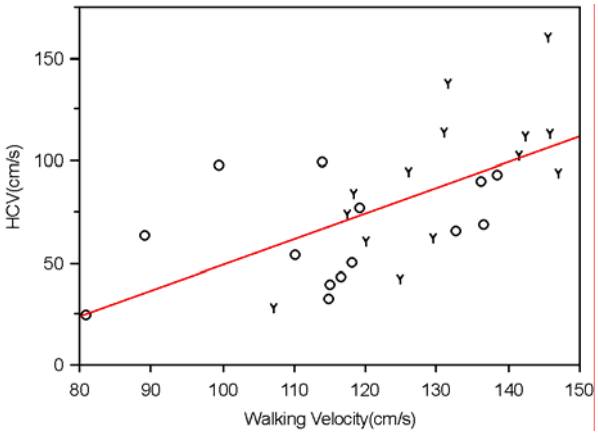

Figure 3. Bivariate Fit of HCV (cm/s) By Walking Velocity (cm/s) (Y: young, O: old)

4. DISCUSSION

The primary objective of the present study was to evaluate if the whole body COM velocity and heel contact velocity could play a role in increasing the likelihood of slips among older adults. Changes in the gait parameters (i.e. heel contact velocity and the whole body COM velocity) have been addressed as suggestions for why older adults are more susceptible to slip-induced falls. Yet, there have been a few studies looking at how heel contact velocity or the whole body COM velocity among the two different age groups (young Vs old) influence RCOF while walking at the preferred walking speed. In the present study, the authors attempted to assess if hypothesized differences in the whole body COM velocity

and heel contact velocity between the two age groups contributed to variations in friction demand characteristics(i.e. RCOF).

Does older adults' whole body COM velocity differ from younger adults' whole body COM velocity, and is the whole body COM velocity related to friction demand?

In agreement with the previous studies(Dobbs et al., 1993; Hageman and Blanke, 1986; Himann et al., 1988; Imms and Edholm, 1981; Rubenstein et al., 1988; Murray et al., 1969; Wall et al., 1991; Trueblood and Rubenstein, 1991), our studies indicated that older adults walked slower than younger adults(120.22cm/s±10.12 Vs 133.23cm/s±11.59). There have been many suggestions for why older adults walk slower. With advancing age, problems exist in delivering sensory feedback and utilizing the feedbacks in musculoskeletal system to coordinate and control the lower extremities during walking. Decrease in muscle strength in association to loss of motor neuron, muscle fibers, and aerobic capacity (Bendall et al., 1989; Trueblood and Rubenstein, 1991) as well as degradations in the auditory, vestibular, visual, and somatosensory system in association to loss of motor units and sensitivity(Delwaide, 1986) were suggested to be associated with an older adults' gait adaptation such as slower the whole body COM velocity (Prince et al., 1997).

In agreement with a study by Lockhart et al.(2003), the present study found that as the whole body COM velocity increased, RCOF increased. In the present study, older adults walked slower than younger adults leading to lower RCOF than younger adults. Characteristics associated with transition of the whole body COM played an important role in the variation of horizontal and vertical foot force components during and after heel contact, and influenced likelihood of slip-induced falls due to the effects of RCOF on the initiation of slip-induced falls (Gronqvist, 1995; Kim and Lockhart, 2004 submitted; Lockhart et al, 2003; Lockhart et al., 2002). After the heel contact, horizontal foot forces continue to increase as the whole body mass progress forward(Lockhart et al., 2003). As indicated by Newton's first law, when mass is the constant, force increases proportionally as velocity increases. While walking, horizontal shear force increases as the whole body COM velocity in the forward direction increases. This results in proportional increases in RCOF(i.e. friction demand). Thus, faster whole body COM velocity seen among younger adults in the present study explained why younger adults exhibited higher RCOF in comparison to older adults.

Despite lower RCOF and slower the whole body COM velocity found among older adults in the present study, other studies reported that older adults are more susceptible to falls than younger adults(Khuvasanont and Lockhart, 2002; Lockhart et al., 2002). The whole body COM velocity was an important factor in predicting balance conditions of the subjects during the whole body COM transition(You et al., 2001; Pai and Patton, 1997). Lockhart et al.(2003) 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 adults exhibited slower transition of the whole body COM(i.e., transitional acceleration of the whole body COM between the heel contacts). This slower transition of the whole body COM of the older adults after the heel contact could explain why older adults' friction demand was higher than their younger counterparts and increase risk of slip-induced falls (Lockhart et al., 2002). Regaining balance after slips initiation could be more difficult for older adults with slower whole body COM velocity than for younger adults with faster whole body COM velocity(Pai and Patton, 1997; You et al., 2001). The authors concluded that although walking faster directly increased the friction demand resulting in the increase in the likelihood of slips, walking faster could play a role in regaining and controlling the balance of the whole body COM while slipping or falling. Although implicated, further study evaluating fall dynamics associated with different walking velocities is needed to elucidate this possibility.

Does older adults' heel contact velocity differ from younger adults' heel contact velocity and is heel contact velocity related to RCOF?

Heel contact velocity was thought to increase the likelihood of slipping due to the alteration of horizontal shear force(i.e. increased horizontal shear force), and was evaluated to predict the likelihood of slip-induced falls(Karst et al., 1999; Lockhart et al., 2003; Myung et al., 1992). As stated previously, younger adults walked faster and had higher RCOF. At the same time, younger adults' heel contact velocity was statistically higher than

older adults in disagreement with the previous studies (Karst et al., 1999; Lockhart et al., 2003; Myung et al., 1992). Nonetheless, in contrast to a study by Mills and Barrett(2001), heel contact velocity was not significantly different between the two age groups when accounting for the effect of the whole body COM velocity. Higher heel contact velocity found in the present study probably could be due to the effect of faster whole body COM velocity, not the effect of age, as confirmed by the analysis of covariance(ANCOVA).

Perkins(1978) suggested that peak RCOF occurred 70~120ms after heel contact. Therefore, rationally, an identification of heel contact velocity may not be an appropriate measurement for predicting slip-induced falls as indicated by the results in the present study during normal level walking considering only the friction demand paradigm. Instead, whole body COM velocity was assessed as a valid measurement for predicting the heel contact velocity and friction demand in the present study. In the present study, walking faster eventually led to higher heel contact velocity resulting in higher friction demand. The suggestion by Winter(1991), and Mills and Barrett(2001) that horizontal heel contact velocity was a critical factor contributing to a risk of slip-induced falls was not found to be significant in the present study since horizontal heel contact velocity did not predict the friction demand, which has been used to evaluate the likelihood of slip-induced falls in general. These results suggested that measuring the whole body COM velocity could better predict friction demand characteristics during normal level walking. In addition, the consistently large variations shown in heel contact velocity(Figure 4) in both younger and older adults may suggested that there were additional factors that may have influenced heel contact velocity besides the whole body COM velocity such as step length and the whole body COM transitional acceleration(Grönqvist et al., 1989; Lockhart et al., 2002 and 2003).

In conclusion, the present study suggested that horizontal heel contact velocity did not show consistent prediction of RCOF for young and old adults. Instead, the whole body COM velocity predicted the likelihood of slip-initiation more consistently. The study further concluded that younger adults' RCOF was higher than their older counterparts due to faster walking velocity(i.e., velocity of the whole body COM), not due to higher heel contact velocity.

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