Industrial Health 2008, **46**, 32–39

Original Article

The Effects of 10% Front Load Carriage on the Likelihood of Slips and Falls

Sukwon KIM[1] **and Thurmon E. LOCKHART**[2*]

[1]Human Factors and Ergonomics Lab, Industrial Engineering and Technology, Texas A&M University-Commerce, Commerce, TX 75428, USA
[2]Locomotion Research Laboratory, Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24060, USA

Received July 28, 2007 and accepted October 22, 2007

Abstract: The objective of the present study was to evaluate if anterior load carriage would increase the likelihood of slips or falls while walking over a slippery floor surface. The study hypothesized that anterior load carriage may alter spatial-temporal characteristics, such as heel contact velocity, walking velocity (i.e., the whole body center-of-mass velocity), and step length, as well as friction demand characteristics at shoe-floor interface. Additionally, the study hypothesized that alterations in these gait parameters may influence slip initiation characteristics while ambulating over a slippery floor surface. Total of 10 subjects participated in the study: 5 younger (18–28 yr old) and 5 older adults (65 and older). A mixture was used to manipulate the coefficient of friction (COF) of the floor surface. All participants were unexpectedly introduced to a slippery surface while walking with and without a load. To evaluate slip severity, slip distance I and II were evaluated to assess whether a subject fell or not. Three-way repeated measure ANOVA (mix-factor design) was performed: Age factor: between-subject, Load and Floor factors: within-subject. Overall, older adults' heel contact velocity was slower while carrying a load. Additionally, all participants exhibited shorter SL while carrying a load. No significant friction demand characteristic differences were observed for all subjects while carrying a 10% front load. The results from the present study suggest that carrying 10% of the body weight in front should not intensify the slip propensity and severity although appears to influence spatial-temporal gait characteristics.

Key words: Load, Walking, Slips, Falls, RCOF

Introduction

Occupational load carrying tasks are considered one of the major factors contributing to slip and fall injuries and the first event/exposure leading to more than 30% of all non-fatal occupational slip and fall injuries resulting in one or more days away from work[1)]. Although implicated in epidemiological assessments, mechanisms and likelihood of slip propensity and severity during work tasks involving load carrying has not been fully investigated. Furthermore, spatio-temporal biomechanical risk factors in association to slip and fall accidents while carrying a front load has not been explored extensively. Studies[2–8)] suggested that spatio-temporal biomechanical characteristics as well as friction demand characteristics (i.e. RCOF) were major predictors for the likelihood of slip-induced falls. Understanding the mechanisms of gait characteristics associated with a front load carriage can allow us to gain an insight into the effective intervention strategies to reduce slip-induced fall accidents at work.

Dangerous forward slips that lead to falls are most likely to occur 70–120 ms after the heel contacts the ground[3, 8)]. It is characterized by the ratio between F_h and F_v and was referred to as "RCOF"[10)]. The RCOF 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 RCOF could be altered because of changes in F_h and F_v. When RCOF

---

*To whom correspondence should be addressed.

is altered due to different external condition such as load carriage, chances for dangerous slip initiation is increased. This dangerous slip initiation can lead to musculoskeletal injuries. Alterations in spatio-temporal characteristics, such as faster heel contact velocity, slower transitional walking velocity, and longer step length, were suggested to increase the RCOF resulting in higher likelihood of falls to occur[4, 11–13]. However, the effects of front load carriage on heel contact velocity, walking velocity, step length, and RCOF over the slippery surface has not been thoroughly examined. In the present study, the risk factors (heel contact velocity, walking velocity, step length, and RCOF) contributing to slip initiation while carrying a load (10%) anterior to the body were evaluated to predict if gait characteristics while carrying a load was different from those while walking normally. More importantly, the study attempted to assess if any changes of these parameters while carrying a load (10%) influenced the slip severity which was measured by the RCOF and slip distances.

Method

1. *Subjects*

Ten individuals from two different age groups participated in the study; 5 younger individuals (18–28 yr old, height (cm); 170.8 ± 5.89, weight (kg); 69.68 ± 7.18) and 5 older individuals (65 and older, height; 174.60 ± 7.06, weight; 80.3 ± 10.89). Each group included 2 females and 3 males. The younger adults were recruited from general student population at Virginia Tech and older adults were recruited from the local community at Blacksburg and Christiansburg, VA. Older adults were included to broaden the effects found in the present study for younger population as well as older population. Each participant completed an inform consent procedure approved by the Virginia Tech Internal Review Board (IRB). Participants were excluded from the study if they indicated any physical problems (i.e. hip, knee or ankle problems). A questionnaire was used as an initial screening tool.

2. *Apparatus and procedure*

A commonly used floor material (vinyl tile, Armstrong) was used in this experiment to represent a realistic environmental setting. A mixture of glycerin and pure water (4:1 ratio) was applied to the floor surface to create slipperiness. Dynamic COF between the floor surface and an experimental shoe was measured using a standard 4.54 kg (10 lb.) horizontal pull slip-meter with a rubber sole material on the force platform (Lockhart *et al*., 2003) and measured to be 0.07 (i.e., to generate a risky or dangerous walking condition or environment). All participants were provided same laboratory shoes with rubber sole (Athletic Footwear) materials to eliminate effects of footwear.

There were two sessions. In the first session, normal walking trials were conducted on a walking track using an overhead fall arresting harness system (Fig. 1). Participants walked at their preferred walking speed from one end of a linear track (15.5 m × 1.5 m) to the other repeatedly. In general, while participants were not looking, an experimenter changed the test floor surface so as to provide unexpected slippery conditions. The trials (i.e., load and no-load; normal and slippery surfaces) were completely randomized. For the load carrying session, participants carried a customized container (43

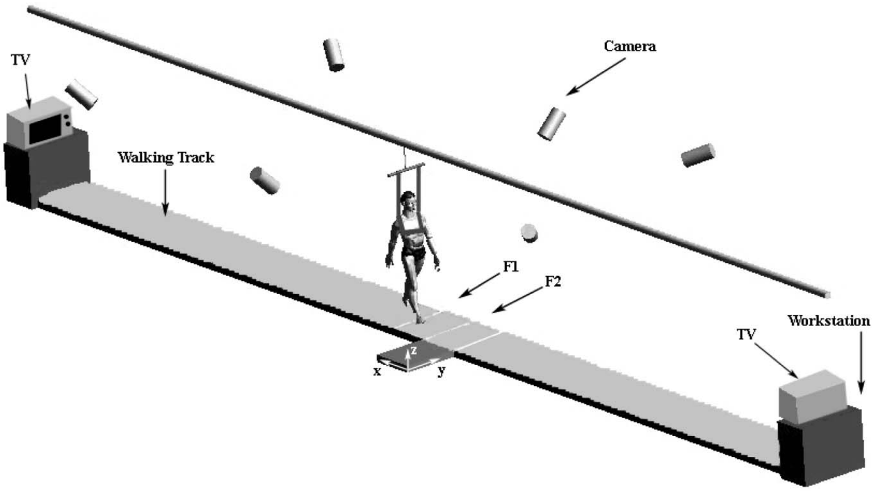

Fig. 1. Field layout of the experimental set-up including; Fall Arresting System, Infra-red cameras (6), Two force plate (F1 and F2), and workstations. X,Y, and Z=global references for force and position. The surface of F2 was used to created slipperiness.

cm × 33 cm × 28 cm) that weighed 10% of their body weight at their waist level. The container had a gray plastic interior with a dark blue quilted nylon case and foam top and a laterally positioned handle on each side, and had a small plywood box (30 cm × 20 cm × 15 cm) to secure weights. The box was positioned in the container enclosed by 10 cm foams in all directions (left, right, upper, and lower sides of it). Participants walked at their preferred speed on the 15.5 m walkway, and rested the load on a table at each end of the track (Fig. 1). While walking, starting point was adjusted so that the participants continuously stepped over the force plate for kinetic assessments (i.e., RCOF). While participants were not looking, an experimenter changed the test floor surface to present unexpected slippery conditions. Normal floor and slippery floor surfaces were mounted to a force plate, and the slippery floor surface was hidden under a track in order to eliminate participants' expectancy on upcoming events (i.e. slipping). The overall function of the system was to control the experimental conditions without participants being aware of any floor surface change. A fall-arresting rig was designed to permit participants to fall approximately 25 cm before arresting the falls and stopping any forward motion.

3. Data Collection and Analysis

The marker coordinate data from ProReflex were used to calculate the gait parameters (step length, horizontal heel velocity, slip distance I and II, and Center of Mass (COM) velocity). Kinematic data were recorded for 5 s at 120 Hz and lowpass-Butterworth-filtered at 12 Hz. Force data were used to determine the required coefficient of friction (RCOF; peak 3 as defined[5, 8]). Ground reaction forces were measured at 1,200 Hz for 5 s on two force-plates and lowpass-Butterworth-filtered at 6 Hz.

Three-way (Age (Young and Old) × Load (Load and No-load) × Floor (Slippery and Dry)) repeated measure ANOVA was performed by utilizing the JMP statistical packages (SAS Institute Inc. Cary, NC, USA). Age factor was a between-subject variable and Load and Floor factors were within-subject variables. The results were considered as statistically significant when $p \leq 0.05$.

4. Dependent Variables

1) Heel contact velocity (HCV)

Heel contact velocity was assessed by the heel marker 1/120 s before and after the heel contact point as defined by the forceplate (greater than 7N was used for this criteria[4, 5]) HCV represented the resultant speed of foot contacting the floor and influenced friction demand characteristics as well as slip-initiation. 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 using the formula:

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

2) Center of Mass Velocity (Synonym: Walking Velocity)

The whole body Center-of-Mass (COM) velocity was a measure of velocity at the body COM and calculated by averaging all of the COM from the 14 segments (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, and head). The COM velocity of all the participants was calculated using the formula:

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

Then, all COM velocities from heel contact to heel contact are averaged to represent walking velocity[5].

3) Step Length (SL)

Step length is a measure of length between heels of each foot during stance phase. The linear distance was measured in the direction of progression between successive points of foot-to-floor contact of the first foot (X_1, Y_1) and other foot (X_2, Y_2). Step length was calculated from the distance between consecutive positions of the heel contacting the floor.

4) 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 the vinyl floor surface[10].

5) Slip Distance I (SD I)

Slip distance was calculated using a heel marker (kinematics) while the foot was slipping; it was a combination of slip distance I and slip distance II as defined by Lockhart *et al.* 2003[4], 2005[5]. SD I was measured to provide information concerning the severity of slip initiation. Slip-start point for SD I was defined as the point where non-rearward positive acceleration of the heel after heel contact, equivalently where the first minimum of the horizontal heel velocity after the heel contact[14]. The slip-stop point for SD I was defined as the point where peak horizontal heel acceleration occurred after the slip-start point.

6) Slip Distance II (SD II)

Slip distance II provided information concerning the slip behavior after the initiation of slips. The start point for the slip distance II was defined from SD I slip-stop point to the end of slip. The end of the slip was estimated as the time where the first maximum of the horizontal heel velocity after slip start point occurred. SD II was calculated from the heel coordinates using the distance between the two points as with SD I.

Result

1. *Heel Contact Velocity*

The ANOVA (Table 1) indicated that there was significant Load × Age interaction. The results indicated that older adults' HCV was faster than younger adults' HCV while carrying no load, although older adults' HCV was not different from young adults' HCV while carrying the load (Fig. 2).

2. *The Whole Body COM Velocity*

The ANOVA (Table 1) indicated that there were no significant main effects and interactions.

3. *SL*

The ANOVA (Table 1) indicated that there was a significant load effect on SL ($F_{1,8}$=5.32, p=0.05). The results indicated that individuals took smaller steps while carrying a load (69.21 cm vs. 65.54 cm, Fig. 3). Additionally, there was a significant load × Age interaction effects (Fig. 4). The ANOVA indicated that older adults' SL was significantly shorter in comparison to younger adults' SL while carrying a load.

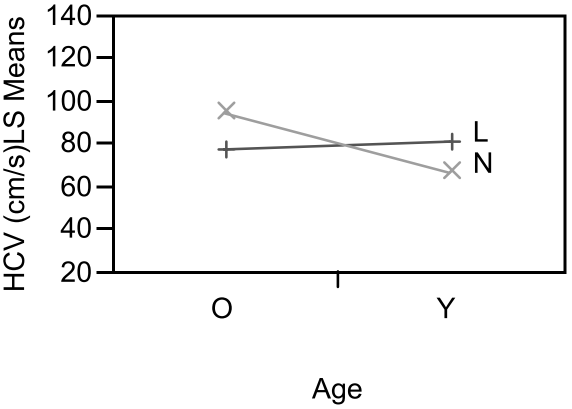

Fig. 2. Least Square Means Plot of HCV by Load x Age (Y: young, O: old, L: load, N: no-load).

Table 1. ANOVA Summary Table

Effects for RCOF			*Effects for HCV*		
Source	F Ratio	Prob > F	Source	F Ratio	Prob > F
Age	3.01	0.12	Age	2.10	0.19
floor	0.00	0.97	floor	2.45	0.16
Age*floor	0.59	0.47	Age*floor	0.15	0.71
Load	1.90	0.20	Load	0.05	0.83
Load*Age	0.29	0.61	Load*Age	5.15	0.05
floor*Load	0.93	0.36	floor*Load	2.22	0.17
Age*floor*Load	0.01	0.92	Age*floor*Load	0.21	0.66
Effects for WV			*Effects for SL*		
Source	F Ratio	Prob > F	Source	F Ratio	Prob > F
Age	0.96	0.36	Age	1.10	0.33
floor	0.73	0.42	floor	0.82	0.39
Age*floor	0.01	0.91	Age*floor	0.05	0.83
Load	0.01	0.91	Load	13.79	0.006
Load*Age	0.16	0.70	Age*Load	8.78	0.02
floor*Load	0.10	0.77	floor*Load	0.00	0.96
Age*floor*Load	0.02	0.89	Age*floor*Load	3.76	0.09
Effects for SD I			*Effects for SD II*		
Source	F Ratio	Prob > F	Source	F Ratio	Prob > F
Age	1.32	0.28	Age	0.09	0.77
floor	2.48	0.15	floor	9.14	0.02
Age*floor	1.35	0.28	Age*floor	0.05	0.83
Load	0.38	0.56	Load	1.12	0.32
Load*Age	0.49	0.51	Load*Age	0.08	0.78
floor*Load	0.39	0.55	floor*Load	1.19	0.31
Age*floor*Load	0.48	0.51	Age*floor*Load	0.07	0.80

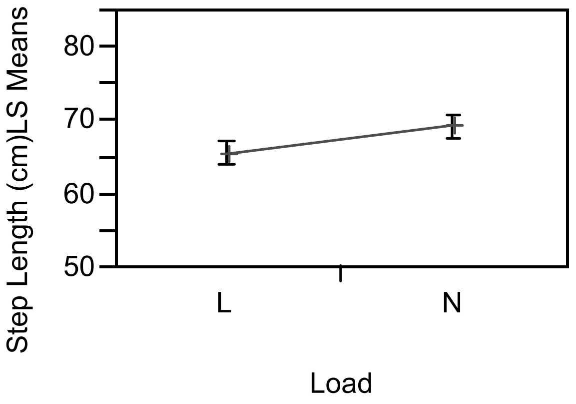

Fig. 3. Least Square Plot SL by Load.

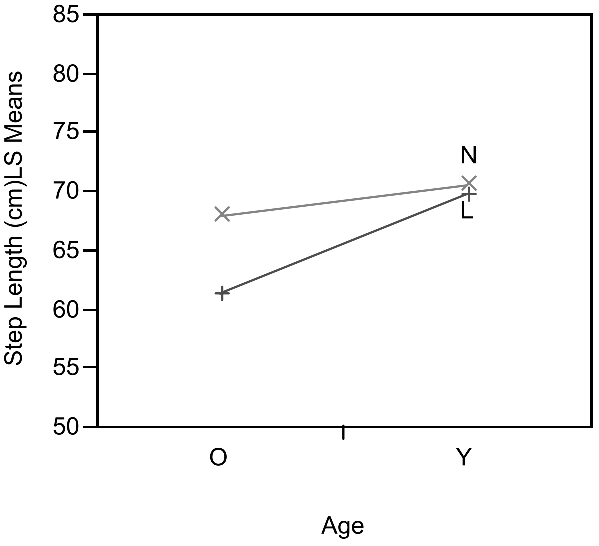

Fig. 4. Least Square Means Plot of SL.

4. RCOF

The ANOVA (Table 1) indicated that there were no significant main effects and interactions.

5. SD I

The ANOVA (Table 1) indicated that there were no significant main effects and interactions.

6. SD II

The ANOVA (Table 1) indicated that there was floor effect ($F_{1,8}$=9.14, p=0.02) on SD II. The result indicated that individual slipped significantly longer when walking over slippery surface (49.34 mm vs. 1.25 mm, Fig. 5). However, no significant load effect was found while carrying a 10% front load.

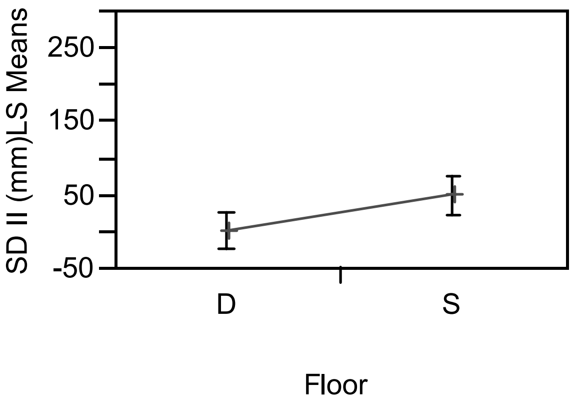

Fig. 5. Least Square Means Plot of SD II by Floor (S: slippery, D: dry).

Discussion

Limited research suggests that front load carriage plays a moderate role in slips and falls although load carriage has been clearly shown to influence biomechanics of gait such as step length[15)] and trunk rotations[16)]. The present study was performed to evaluate if carrying a load in front would impair temporal-spatial gait characteristics (HCV, WV, and SL) and would influence slip severity (RCOF and SD I and II), and, ultimately, predisposed to slip-induced falls.

1. Spatio-temporal Characteristics

Examining the spatio-temporal gait characteristics is the initial stage in evaluating human locomotion when there is little information available to construct further investigations. The initial findings throughout spatio-temporal characteristics in the present study would be helpful in more sophisticated gait assessments such as joint torque and muscle force assessments. In the present study, older adults' HCV was faster while carrying no-load in comparison to younger adults' HCV, whereas, there was no difference while carrying the load (older vs. younger, Load: 77. 22 cm/s vs. 80.90 cm/s, No-load: 94.95 cm/s vs. 66.50 cm/s). In other words, there was no different in HCV between two populations when carrying load (older adults' HCV when carrying load was significantly slowed down while younger adults' HCV was amplified) although older adults' normal HCV was generally faster than younger adults[4, 6)]. This result in the study may also have indicated that healthy older adults may have not been concerned of slips and falls while their normal walking in this study. Nevertheless, the results may indicate that, while carrying a load, older adults reduced heel velocity sufficiently at the heel contact phase of the gait cycle to avoid unexpected events such as slipping due to fear for unexpected events[17)]. Moreover, older adults may have struck their foot slower to the ground at the time of heel contact while carrying a load due to the time required to overcome the inertial forces due to an added weight. This may have slowed down the whole body COM progression resulting in slower HCV[4, 18)]. Shorter step length among older adults while carrying a load further supported this statement. Inability to bring their COM forward while carrying a load during the swing phase resulted in older adults taking a shorter step. This may be resulted by physiological aging process such as strength degradations seen in older adults such as ankle strength degradation[19, 20)]. Inability to progress forward the whole body COM when carrying an additional weight may induce the slower HCV among older adults as well as the shorter SL. More interestingly, this possible adaptation would leave the supporting leg in a danger since additional weight would be left in the supporting leg while the swinging leg would not be in contact with the floor. This suggested that, while carrying a load, risks may be greater in the supporting foot slips. This statement is further supported by the fact that most slips while carrying a load started at 8% of gait cycle, whereas, most slips while carrying no-load started at 5% of gait cycle in the present study. Further study in evaluating the effects of load carrying in front on the supporting leg should be performed to evaluate if the likelihood of slip-induced falls could be more dangerous at the contacting foot when the other foot begins swing phase of the gait cycle.

While older adults exhibited precarious gait while carrying a load (i.e., slower HCV), their younger counterparts exhibited compensatory gait behavior wherein heel contact velocity was increased. Compensatory behavior may be related to efforts to optimize the gait pattern for energy efficiency, maximum speed, or other criteria such as stability while carrying a load[26)]. Although implicated, further study is necessary to identify optimal gait patterns while carrying a load on various environmental conditions to elucidate occupational relevance.

Shorter SL while carrying the load may be induced by the mechanism caused for slower HCV[15)]. Decreased SL was indicated to lessen the likelihood of slip-induced falls because it tended to reduce the horizontal shear force in proportion to the vertical force at the shoe-floor interface resulting in smaller RCOF during heel contact[3–5)]. In disagreement with these previous findings, the results from the present study suggested that shorter SL while carrying 10% of body weight did not influence RCOF: the RCOF was expected to decrease as SL was decreased due to reductions in horizontal shear forces at heel contact. The disagreement between the present study and the previous studies may be due to the fact that the time required to overcome the inertia at their COM was slower which led to slower transition of the COM during heel contact; authors speculated that the COM acceleration during heel contact velocity would become slower while carrying a load . This slower transition of the COM may have indirectly influenced the proportional increase in horizontal shear force, therefore, evening out the forces between horizontal and vertical directions[4, 18)]. Authors suggest performing further studies to verify the effects of load carrying on the transition of the whole body COM (i.e., the whole body COM acceleration during heel contact phase of the gait cycle).

2. Slip Severity (RCOF and Slip Distance I and II)

Slip severity measures (RCOF and Slip distance) have been used to predict the likelihood of slip-induced falls[3–6, 8, 10, 14, 18, 19, 21)]. It was suggested that greater the RCOF and longer the slip distance, lesser chance to recover from slipping, resulting in falls[3, 4)]. But there has not been enough effort to understand the effects of load carrying on the RCOF. The present study evaluated slip severity while carrying a load in front to assess if carrying load could aggravate slip severity.

The results indicated that carrying 10% of body weight did not intensify changes in the RCOF as well as slip distance although the force data in the present study indicated that horizontal force and vertical force increased in proportional to the load in agreement with a previous finding[22)]. These corresponding increases both in horizontal and vertical forces may deteriorate the effects of load carrying on the friction demand characteristics (i.e. the RCOF). This result suggests that carrying a 10% of body weight in front should not influence slip severity (i.e. the RCOF and slip distance) although it may have influenced the spatio-temporal characteristics of human gait such as shorter SL and changes in HCV.

Previous studies[23, 24)] suggested that carrying a 10% of body weight did not change the biomechanical and physiological parameters (stride and temporal parameters, trunk lean angles, trunk motion range, and heat beat recovery time). In agreement with the previous studies, our study indicated that carrying a 10% of body weight in front should not influence gait characteristics and slip initiation characteristics. This further suggests that carrying a 10% of body weight does not increase the likelihood of slip-induced falls. In conclusion, the results in the present study support that carrying 10% of body weight in front is an acceptable method at work when accounting for the likelihood of slip-induced fall.

Limitations

Findings from the current study only applies to an event which represents the effects of a load in front of the body, which weighs 10% of body weight, on spatio-temporal characteristics of gait while walking over slippery surfaces. However, the study assumed that cases for slip-induced falls for industrial works usually are fairly dependent on the weight of load they are carrying. Authors attempted to test the effects of loads that weighed more than 15% of body weigh. However, authors found that carrying those loads (15%, 20%, 25%, and 30%) at participants' preferred walking speed varied so frequently that authors were not able to get their foot correctly on force plates with numerous attempts. Authors concluded that walking at the preferred walking speed with more than 15% of body weight could lead to higher variances in gait parameters as well as slip parameters such as the RCOF and slip distance resulting in the higher likelihood of slip-induced falls. Authors may have evaluated participants' gait and slip parameters by utilizing the one-step test while carrying load that weighed over 15% of their body weight in stead of natural walking. However, authors for the present study concluded that the one-step test may not depict the actual gait parameters as well as slip parameters while carrying a load. The main purpose of the study was to provide the initial gait characteristics while carrying a front load to, further, investigate more sophisticated parameters. Authors will attempt to find an optimal method to evaluate the effects of a front load carriage at 20% and 30% of participant' body weight on the likelihood of slip-induced fall in future.

It is well known that one's strength is significantly dependent upon his/her body mass. This may suggest that one's ability to carry a load also depends on his/her body mass. In this study, gender effects on physical characteristics were not tested because the effects of weight were minimized by employing a proportional weight (10% of the body weight) for each individual. Still, it has been suggested that significant number of falls among the elderly female were reported in comparison to the elderly male[25]. Although implicated, in this study gender effect was not included as an explicit independent variable since most reports have failed to find gender differences in occupational falls[26].

References

1) Courtney T, Webster B (2001) Antecedent factors and disabling occupational morbidity insights from the new BLS data. Am Ind Hyg Assoc J **62**, 622–32.
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**, 979–95.
3) Grönqvist R (1995) A dynamic method for assessing pedestrian slip resistance. Finnish Institute of Occupational Health, Helsinki, Research Report 2.
4) Lockhart TE, Woldstad JC, Smith JL (2003) Effects of age-related gait changes on biomechanics of slips and falls. Ergonomics **46**, 1136–60.
5) Lockhart TE, Kim SW (2005) Relationship Between Hamstring Activation Rate and Heel Contact Velocity: Factors Influencing Age-Related Slip-Induced Falls. Gait Posture **24**, 23–34.
6) Mills PM, Barrett RS (2001) Swing phase mechanics of healthy young and elderly men. Hum Move Sci **20**, 427–46.
7) Pai YC, Patton JL (1997) Center of mass velocity-position predictions for balance control. J Biomech **30**, 347–54.
8) Perkins PJ (1978) Measurement of slip between the shoe and ground during walking. American Society of Testing and Materials, Special Technical Publication 649, 71–87, ASTM International, Philadelphia.
9) Winter DA (1991) Biomechanics and Motor Control of Human Movement, 2nd Ed., Wiley & Sons, Toronto.
10) Redfern MS, 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.
11) James DI (1983) Rubber and plastics in shoe and flooring: The importance of kinetic friction. Ergonomics **26**, 83–9.
12) Myung R, Smith JL, Leamon TB (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.
13) Soames RW, Richardson RPS (1985) Stride length and cadence: Their influence on ground reaction forces during gait. International Series on Biomechanics IXa, 406–10.
14) Lockhart TE, Woldstad JC, Smith JL (2002) Assessment of Slip Severity Among Different Age Groups, ASTM STP 1424, Metrology of Pedestrian Locomotion and Slip Resistance. American Society for Testing and Materials, Pennsylvania.
15) Martin J, Nelson R (1986) The effect of carried loads on the walking patterns of men and women. Ergonomics **29**, 1191–202.
16) LaFiandra M, Wagenaar RC, Holt KG, Obusek JP (2003) How do load carriage and walking speed influence trunk coordination and stride parameters? J Biomech **36**, 87–95
17) Davis T, Lockhart TE (2003) The Effects of Age on Stress and The Biomechanics of Slips and Falls. In: Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting, October 13–17, Denver Colorado USA, Industrial Ergonomics, Stability and Gait, 1131–5.
18) Kim S, Yoon H, Lockhart T (2006) Comparison of spatio-temporal characteristics between young and old adults while walking: factors influencing the likelihood of slip-initiation. J Ergon Soc Korea, **25**, 43–9.

19) Khuvasanont T, Lockhart TE (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, 1–5.
20) Judge J, Davis R, Ounpuu S (1996) Step length reductions in advanced age: the role of ankle and hip kinetics. J Gerontol **51**, 303–12.
21) Lockhart TE, Smith JL, Woldstad JC (2005) Effects of aging on the biomechanics of slips and falls. Hum Factors **47**, 708–29.
22) Tilbury-Davis and Hooper (1999) The kinetic and kinematic effects of increasing load carriage upon the lower limb. Human Movement Science **18**, 693–700.
23) Hong Y, Brueggemann GP (2000) Changes in gait patterns in 10-year-old boys with increasing loads when walking on a treadmill. Gait Posture **11**, 254–9.
24) Hong Y, Cheung C (2003) Gait and posture responses to backpack load during level walking in children. Gait Posture **17**, 28–33.
25) Stevens JA, Sogolow ED (2005) Gender differences for non-fatal unintentional fall related injuries among older adults. Inj Prev **11**, 115–9.
26) Collins JJ (1995) The redundant nature of locomotor optimization laws. J Biomech **28**, 251–67.
27) Courtney TK, Sorock GS, Manning DP, Collins JW, Holbein-Jenny MA (2001) Occupational slip, trip, and fall-related injuries— can the contribution of slipperiness be isolated? Ergonomics **44**, 1118–37.