

## PREDICTION OF FALLS USING A ROBUST DEFINITION OF SLIP DISTANCE AND ADJUSTED REQUIRED COEFFICIENT OF FRICTION

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This paper proposes a new method to identify slip distance and adjusted required coefficient friction to predict falls among different age groups. These methods were based on the fact that the dynamics of slips are altered due to the fall arresting rig (or harness) during the critical moment of slips and falls.

### INTRODUCTION

Reducing slip and fall accidents has been a topic of interest to many researchers since the 1920s. Traditionally, these researchers utilized four basic approaches to investigate slip and fall accidents; epidemiology, biomechanics, tribology and psychophysics. However, in spite of the improvements in tribometric techniques to assess shoe/floor interactions, and increased knowledge of the biomechanical responses to walking on slippery surfaces, fall accidents continue to represent a significant burden to society, both in terms of human suffering and economic losses. Furthermore, with the general increased life expectancy and increased proportion of the aged workforce as the major segment of overall population (45 to 65 year olds – WHO, 1993), the workplace is likely to experience a greater risk for slip and fall accidents and may have an additional impact on the economics of the health care system and the industries.

A review of literature on slip and fall accidents indicates that multiple mechanisms are involved in slip and fall accidents. In general, fall accidents on level walking surfaces are believed to be the result of a loss of traction between the shoe and the contact surface. The term "slip" has often been used to describe this loss of traction, both when the slip results in a fall and when it does not (Miller, 1983). Recently, slip classifications have been used as a measure of floor surface slipperiness (i.e. severity of slips). In addition to interest in slips and microslips as potential indicators of slipperiness, gait parameters (such as RCOF) at the point of initial foot contact are of interest for tribological studies (Perkins, 1978; Perkins and Wilson, 1983).

In terms of biomechanical approach to prevention of slips and falls, main attention has been focused on studying of slip behavior of the young individuals. Slip behavior has been investigated by many researchers (Perkins, 1978; Strandberg and Lanshammar, 1985; and Leamon and Son, 1989). Actual slip experiments were conducted on subjects wearing test shoes, walking from non-slippery surfaces onto slippery surfaces utilizing a fall arresting rig (and harness) to prevent injuries. In the majority of experiments, slips occurred in a forward direction having started shortly after the heel contacted the contaminated surface. In some cases the shoe only slipped a few centimeters and then stopped, so that the subjects were able to regain balance and continue

walking. In other cases, the foot continued slipping, and the subjects were unable to recover balance. The severity of a slip (whether the slip resulted in a fall) therefore, appears to be dependent on the distance through which subjects slipped (for example, any slip more than 10 to 15 cm in length resulted in loss of balance). Perkins (1978) noted that this effect (slip) is probably related to the acceleration of the foot as it slips forward. He further noted that if the foot travels faster than the body, the body can never catch up, but if the body is able to overtake the slipping foot (whole-body-center-of-gravity speed is greater than the slipping speed of the foot), the frictional force will be increased and therefore, the slip will come to a halt.

Although the above concepts are sound and logical, currently, there exist no universal definitions (nor the robust technique) for assessing slip severity for different age groups (i.e. slip distance, foot acceleration, etc). The purpose of this study was to develop a method to assess slip severity among different age groups. This was accomplished by closely examining the slip behaviors of individuals from three different age groups (young, middle, and elderly), and defining the repeatable gait patterns during the event of slips and falls. It was also to investigate the process of initiation and recovery of inadvertent slips and falls among different age groups utilizing new technique for assessing slip severity (for more detailed description of this result, please see Human Factors Proceeding titled: *Effects of Musculoskeletal and Sensory Degradation due to Aging on the Biomechanics of Slips and Falls*). In this report, the former will be explained in more detail. It was hypothesized that slip severity will be different among three age groups due to the intrinsic changes (i.e. muscle weakness, sensory degradation, etc) associated with aging.

### METHOD

*Subjects.* Fourteen young individuals (7 male and 7 female), 14 middle-aged individuals (7 male and 7 female), and 14 older individuals (7 male and 7 female) participated in this experiment. Subject's age, height and weight information is presented in Table 1.

Table 1. Subject information

	Young (18-29 yrs.) Mean (S.D.)	Middle (35-59 yrs.) Mean (S.D.)	Old (65 yrs. and over) Mean (S.D.)
Age (yr)	22.6 (2.1)	46.9 (13.6)	75.55 (6.76)
Ht (cm)	169.7 (6.1)	173.5 (6.3)	170.2 (6.4)
Wt (kg)	68.7 (9.6)	75.5 (16.1)	76.8 (13.3)

The young subjects were recruited from the general student population at Texas Tech University and older subjects were recruited from local community. All participants were compensated for their time and effort.

*Apparatus and Procedure* (for more detailed description, please see Human Factors Proceeding titled: *Effects of Musculoskeletal and Sensory Degradation due to Aging on the Biomechanics of Slips and Falls*).

*Treatment of Data.* The converted coordinate data for each of the 26 body markers (defining a 14-segment whole body model [MacKinnon and Winter, 1993]) and the ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter (Winter, 1990). Residual analyses of the difference between the filtered and unfiltered signals over three different cutoff frequencies (6, 10, and 12 Hz) determined 6 Hz as the preferred cutoff frequency. The dependent measures (vinyl tiles only), adjusted RCOF (ARCOF), slip distance (SD), sliding heel velocity (SHV), heel acceleration, and estimated center of gravity velocity of the whole body (COGV) during slipping were analyzed by 3 x 2 (age x load) two-way repeated measures analyses of variance with  $\alpha = 0.05$ . For this analysis load were treated as a within-subjects effects, while age was a between-subjects effect. The p-values in the ANOVA were adjusted for violations of the assumptions regarding the variance-covariance matrix using the Huynh-Feldt method to estimate  $\epsilon$  and adjusting the degree-of-freedom accordingly (Winer et al., 1991). In addition, constant variance and normality assumptions were verified using residual analysis and normality plots. A computer algorithm was written in the C++ 6.0 to objectively determine the dependent measures.

**Calculations of Dependent Measures**

Figure 1 illustrates a typical slip behavior starting from the heel contact point. Heel contact was defined as the time when the vertical ground reaction force (GRF) exceeded 10N (to synchronize kinetic and kinematic variables, a LED was coupled to the vertical force output of the force plates, when the force exceeded 10N, a LED was triggered).

Initially, as indicated by horizontal heel positions, the heel does not slip forward (horizontal heel velocity decreases as the heel quickly decelerates during this time period). This is (no slip) believed to be the result of the position of the whole body COG (closer to the other stance foot) (MacKinnon and Winter, 1993) during the heel contact phase of the gait cycle.

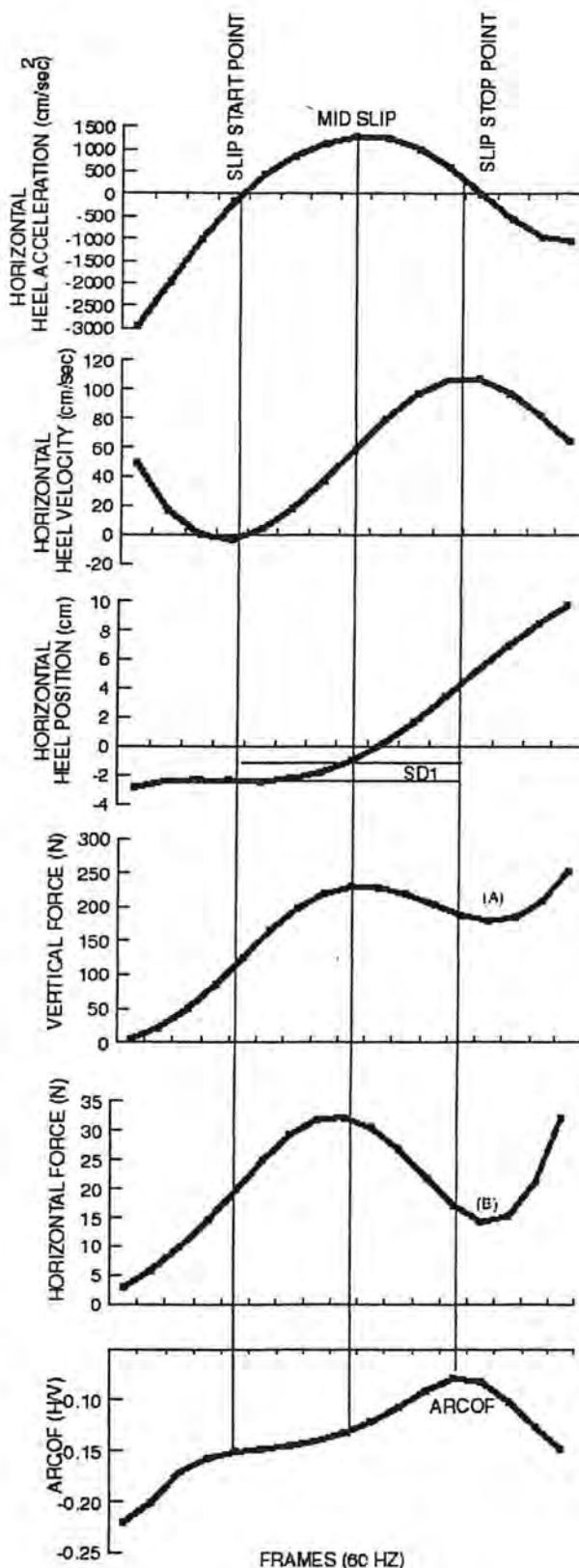


Figure 1. Composite view of the gait parameters.

Shortly after heel contact (approx. 60 ms) (as the fore foot comes down and COG shifts towards the sliding heel), heel begins to slip forward. Afterwards, sliding heel reaches maximum velocity. During this slipping period, the heel accelerates reaching the maximum near the mid point of the sliding heel velocity profile.

After reaching maximum heel velocity, the sliding heel velocity decreases to minimum, halting further slipping (not complete on the Figure 1).

**Slip Distance.** Strandberg and Lanshammar (1981) identified slips by examining the coordinates of the heels. They defined the skid start as the first minimum in heel forward velocity, however, they did not mention how to determine slip stop point. Perkins (1978), also did not specify how to determine the slip stop and slip start, instead presented multi-image photograph of heel slip using a stroboscope. Son (1990), utilizing 3-d coordinates of the reflectors on the subjects, identified slip start as the point at which a change in the horizontal displacement continued at a constant position in the vertical axis (the first minimum of the vertical heel velocity after the heel contact the floor surface), and the slip stop as the point at which change in vertical axis occurred, without a change in horizontal axis (the first minimum of the horizontal heel velocity after slip start point). While Son's definition is much clearer than the others, we found alteration of the vertical force profile in most of our data beyond the point of maximum horizontal heel velocity. Slip and fall experiments usually require a fall arresting rig to prevent injuries. However, a fall arresting harness may affect the outcome of the slips beyond a certain point. Figure 1, illustrates this concept. Point (A) of the vertical force profile illustrates that there is a big decrease in vertical force as the subject slips (after reaching peak heel sliding velocity). This decrease in vertical force may have resulted when the subject tried to compensate for a slip by utilizing the fall arresting harness, and in the process also, may have affected the horizontal force profile (point B). Thus, beyond the peak heel velocity point, the fall arresting harness may affect the biomechanical parameters of slip severity (such as slip distance, slipping velocity etc).

Utilizing the above concept, we defined the slip start point as the time where the first minimum of the vertical heel velocity after the heel contact occurred (a non-rearward positive acceleration-due to the slight rearward displacement occurring after the heel contact), and slip stop point as the time where the first maximum of the horizontal heel velocity after slip start point occurred (point before deceleration, Figure 1).

**Adjusted Required Coefficient of Friction (ARCOF).**

ARCOF is the measured ratio of the horizontal foot force to the vertical foot force at the slip-stop point and represents the ability to adjust dynamic frictional requirements during slipping. The significance of this ratio is that it indicates where in the gait profile compensation for a slip is most likely occur. Figure 1 illustrates this concept. As the horizontal heel velocity reaches maximum, horizontal force is decreased (slight decrease in vertical force as well), thus,

the ratio of horizontal to vertical force profile decreases. At this point, if ARCOF is higher than the available dynamic coefficient of friction (ADCOF), the heel will continue to increase in velocity, however, on this data, ARCOF is lower than the ADCOF, and the horizontal heel velocity decreases (beginning of halting a slip).

**Sliding heel velocity.** The relative sliding heel velocity (SHV) of the heel after heel contact was calculated by averaging the velocity of the heel during the slip start and slip stop points.

**Heel acceleration.** The relative heel acceleration (Hacc) of the heel after heel contact was calculated by averaging the acceleration of the heel during the slip start and slip stop points.

**Center-of-gravity (COG) velocity.** The estimated whole body horizontal COG velocity during slipping (slip start and slip stop point) was calculated utilizing 14 segment whole body model defined by MacKinnon and Winter (1993).

## RESULTS

Lockhart (1997) reported that elderly individuals could not reduce the adjusted RCOF (ARCOF) to available dynamic COF as well as younger subjects on slippery floor surfaces (oily vinyl tile). Consistent with previous findings, older individuals ARCOF was significantly higher than younger counterparts ( $F(2,39) = 13.434, p = 0.0001, \epsilon = 1.053$ ). Table 2 summarizes the mean values and standard deviations for each of the dependent measures as a function of age.

The horizontal distance traveled by the foot (SD) after the heel contact phase of the gait cycle was measured utilizing heel coordinates between slip-start and slip-stop points on the vinyl floor surfaces. Older individuals SD was longer on the average than the younger counterparts ( $F(2,39) = 9.115, p < 0.001, \epsilon = 1.053$ ).

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

Older individuals heel acceleration was significantly faster than younger individuals ( $F(2,39) = 5.448, p < 0.008, \epsilon = 1.053$ ).

Older individuals COGV was significantly slower than the younger counterparts ( $F(2,39) = 3.632, p < 0.035, \epsilon = 1.053$ ).

Table 2. Summary of the gait parameters.

Variables	Young Mean (S.D.)	Middle Mean (S.D.)	Elderly Mean (S.D.)
ARCOF (vinyl)	.074 (.01)	.10 (.01)	.12 (.01)
SD (cm)	4.98 (4.8)	7.65 (4.9)	11.80 (9.4)
SHV (cm/s)	44.05 (35.1)	63.95 (31.7)	74.14 (39.7)
COGV (cm/s)	115.9 (17.4)	123.2 (20.4)	107.3 (16.7)
Hacc (cm/s <sup>2</sup> )	609.5 (79.2)	907.8 (73.5)	912.1 (66.6)

**DISCUSSION**

This research project was undertaken in part to establish a more robust definition of slip severity and, to provide better understanding of dynamics of slips and falls among different age groups. To do this, we compared velocity of COG of the whole body during slip, and sliding heel velocity to identify falls associated with slipping (fall index - whenever the average SHV was greater than the average COGV a fall was defined). The result of fall index is illustrated on Figure 2.

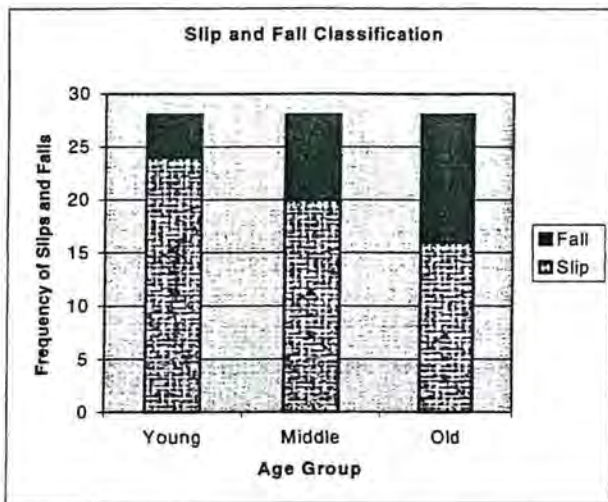


Figure 2. Frequency of slips and falls among different age groups.

Utilizing the fall index and comparing with newly defined slip definitions, we found that exceeding certain limits of SHV, SD1 (slip distance between slip start and peak acceleration point [mid slip on Figure 1]) and heel acceleration resulted in falls (Table 3).

Table 3. Slip recovery index across three age groups.

	SHV(cm/s)	SD1 (cm)	Hacc (cm/s <sup>2</sup> )
Young	144.45	3.91	1580
Middle	145.26	3.80	1310
Old	107.63	3.12	1220

In general, when the subjects in each age group exceeded the recovery index limits, a fall resulted. The younger individuals recovery index was higher on the average and suggest that the recovery index (or slip severity) is not all same for the different age groups. Thus, in a given situation, the older individuals are at a higher risk for fall accidents. This result is further supported by higher ARCOF. On the average, the younger individuals ARCOF (.074) was adjusted within the dynamic friction requirements (.08). However, on the average, middle (ARCOF - .10) and older

individuals (ARCOF - .12) could not. Consequently, the result was longer slip distance and increased frequency of falls.

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# PREFACE

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