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The Effects of Gender, Age, Weight, and Height on Biomechanical Properties Related to Slipping

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Abstract

The friction between the shoe and floor, as measured by the coefficient of friction (COF), is predictive of slip and fall accidents. Developing COF tests requires a comprehensive understanding of the under-shoe mechanics during gait. This study assessed the effects of gender, age, weight, and height on the dynamics of slipping. The gait patterns of 22 older adults (14 female) and 11 younger adults (7 female) were recorded as they experienced an unexpected slip. Under-shoe mechanics (force, shoe angle, and sliding speed) were recorded at the moment when the foot began to slip. Increased height was correlated with increased normal force (p=0.0121) and shoe angle (p=0.0054) but not with sliding speed. Gender, age group, and weight did not significantly affect any of these variables. The COF of the shoe is known to be sensitive to normal force and shoe angle, indicating that individuals of different heights may experience different slip risk.

1. Introduction

Slips and falls are considered to be a significant cause of injury. According to the Bureau of Labor Statistics, in 2016, 26% of nonfatal occupational injuries were caused by slips, trips, and falls (BLS, 2016). Slips and falls are also categorized as among the most costly compensation claims, accounting for $43,035 per compensation claim between 2011 and 2012 (NSC, 2015). Understanding the factors that affect slips and falls are extremely important for preventing these injuries. It has been shown that the coefficient of friction (COF) between the shoe and the floor surface is an important predicting factor when analyzing slips. COF is defined as the ratio of the normal force exerted during walking to the shear force. If the available coefficient of friction (ACOF) is less than the required coefficient of friction (RCOF) that is utilized when walking, then the chances of slipping increase (Burnfield & Powers, 2006). Common techniques and apparatuses for measuring COF sometimes attempt to mimic the under-shoe conditions of gait or slipping (Strandberg & Lanshammar, 1981) (Beschorner K. , Redfern, Porter, & Debski, 2007). This strategy is important since COF values are known to vary based on conditions such as shoe-floor angle, slipping speed, and sliding velocity. However, these conditions are not the same across all individuals. Based on differences in personal attributes that affect slipping dynamics, COF tests can be modified to enable realistic, individualized COF tests. These individualized tests can be useful when evaluating the risk of slips for shoes that are already worn. In addition, results of these tests can yield more effective methods of preventing slips. However, a gap in the literature currently exists regarding whether individual anthropometry can predict under-shoe conditions during slipping.

The goal of this research study was to analyze how various personal factors, such as height, weight, gender, and age, may alter the under-shoe parameters during slipping. It is hypothesized that the under-shoe mechanics of interest (applied force, shoe angle, and sliding speed) will be affected by certain individual factors.

2. Materials and Methods

2.1 Participants

Eleven young participants (seven females and four males) and twenty-two older participants (fourteen females and eight males) were recruited for this study (Table 1). The older adults were older ($t_{31} = 21.7$, $p < 0.001$) and heavier ($t_{31} = 2.7$, $p = 0.01$) but had similar height ($t_{31} = 0.61$, $p = 0.54$) relative to the younger group.

Table 1: Subject's gender, age, weight, and height. The abbreviation, SD, represents standard deviation.

	n	Age (years)		Weight (kg)		Height (cm)	
Gender		Mean	SD	Mean	SD	Mean	SD
Younger subjects							
Male	4	24	0.7	72.5	4.2	175.0	2.8
Female	7	25	0.4	63.0	8.2	166.1	4.5
Older subjects							
Male	8	57	5.6	87.5	13.0	176.3	4.7
Female	14	55	3.3	79.8	17.0	163.7	4.9

Subjects were recruited from the general community. To determine eligibility, subjects were screened and excluded if they had any pulmonary, orthopedic, or neurological conditions, and/or if they had any other condition(s) that would affect normal walking.

2.2 Procedure

All subjects were informed of the testing expectations and potential risks during the written consent process approved by the University of Pittsburgh Institutional Review Board. If the subject was of child-bearing potential, then she was also required to undergo a pregnancy test with a positive test leading to exclusion from the study.

Subjects were fitted with a full-body harness before attaching 79 reflective markers to the bony landmarks of interest. An 8-camera (M2, Vicon Motion Systems, Oxford, UK) motion measurement system collected marker data at a sampling rate of 120 Hz, and two force plates (4060a, Bertec Corporation, OH, USA) collected ground reaction forces at a sampling rate of 1,080 Hz. Floor tiles were cut and attached to the embedded force plates to match the surrounding flooring. The lights were dimmed to reduce the visibility of any contaminant on the surface. To exclude variability in shoe type, all subjects were given the same polyvinyl-chloride-soled shoes to wear during testing. The shoe was an Oxford-style shoe with a 16 mm raised heel. Subjects selected a shoe with a good fit between the sizes of 7 and 13.

Before collecting data, the subjects were instructed to walk down the walkway while focusing on a target attached to the wall in front of them to familiarize themselves with the harness system and lab setting. Once the subject's gait normalized to a comfortable pace, they were told to line up at the start position and wait for the investigator to give starting directions. The goal during the trials leading up to the slip trial, or the baseline dry trials, was to collect ground reaction forces and make sure that the subject was walking at his/her normal pace. In between the baseline dry trials, the subject was asked to turn away from the walking path and listen to music for one minute. This was done to distract the subject so that they would be unaware of the contaminant being placed on the floor prior to the slipping trial.

Three baseline trials with a dry floor were recorded. Following these trials, a contaminant (75% glycerol, 25% water) was spread over the second force plate to cause the subject's left foot to slip. Data was excluded if the foot landed outside of the force plate or if the subject saw the contaminant.

2.3 Data Analysis

The heel contact, toe off, and applied force values for each subject were calculated using filtered ground reaction forces from three good baseline dry trials. A force threshold of 25 N was used to identify heel contact (Cham & Redfern, 2002).

The shoe angle, sliding speed, timing of slip onset, and slip distance were estimated using the marker data. Speed values were calculated by using two-time step differentiation (Cham & Redfern, 2002). The slip distance was determined by finding the first and second local minima after heel contact to establish the slip start and stop, respectively (Lockhart, Smith, & Woldstad, 2005) (Beschorner, Albert, & Redfern, 2016). If the slip distance was greater than 30 mm, then the subject was considered to have slipped (Leamon & Li, 1990).

Statistical analyses were used to examine the impact of individual factors on the under-shoe parameters of interest. The goal of these analyses was to quantify the relationship between under-shoe parameters and simple individual anthropometry parameters. To achieve this goal, simple linear regression analyses were used to investigate the relationship between weight or height and the applied force, shoe angle, and sliding speed. Furthermore, differences between the gender and age groups were performed using independent t-tests. All tests included a Type 1 error rate of 0.05 using a Bonferroni correction for the multiple individual factors that were tested (α=0.05/4=0.0125). To meet the regression assumptions of normally distributed residuals and linearity, the angle was square transformed, while the sliding speed and force were log transformed.

3. Results

Height was correlated with higher applied force values (t_{31}=2.67, p=0.012, r = 0.44); each centimeter (cm) of additional height resulted in a 4.4% increase of applied force (Eq. 1; with force in N and height in cm) (Figure 1). The mean force was 186 N. Force was not correlated with weight (t_{31}=0.97, p=0.340, r = 0.17). Force was also not different across the genders (t_{31}=−2.46, p=0.020) or age groups (t_{31}=1.39, p=0.170). Shoe angle also correlated with height (t_{31}= 2.99, p = 0.0054, r = 0.47, mean angle = 26.7°). Specifically, subjects of greater stature correlated to higher shoe angles (Eq. 2; with angle in degrees and height in cm) (Figure 2). Shoe angle was not correlated with weight (t_{31}=−0.87, p=0.391, r = -0.14) and was not different across the genders (t_{31}=-2.46, p=0.020) and age groups (t_{31}=0.15, p=0.880). Speed was not correlated with height (t_{31}=−0.14, p=0.890, r = -0.22) or weight (t_{31}=−1.31, p=0.199, r = -0.03), nor was it different across the gender (t_{31}=−0.37, p=0.710) or age groups (t_{31}=2.03, p=0.053) (mean speed = 0.13 m/s).

$$ForceNormal=0.124*e0.043*height \quad \text{Eq. (1)}$$

$$Shoe\ Angle= -2540+19.9*height \quad \text{Eq. (2)}$$

Table 2: Statistical results of the regression between height, weight, gender, and age group on force, speed and angle. Significant results are in bold.

	log(Force)		log(speed)		(angle)^2	
	t_{31}	p	t_{31}	p	t_{31}	p
Height	**2.7**	**0.012**	-0.14	0.89	**2.99**	**0.005**
Weight	1.0	0.34	-1.31	0.20	-0.87	0.39
Gender	-2.5	0.019	-0.37	0.71	-2.46	0.02
Age group	1.4	0.17	2.03	0.05	0.15	0.88

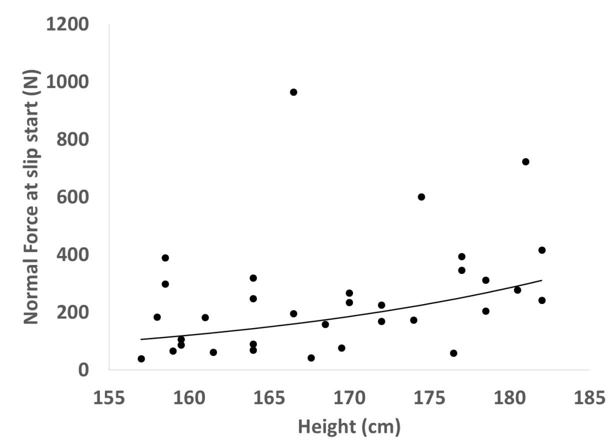

Figure 1: Influence of the subject's height on the normal force at slip-start.

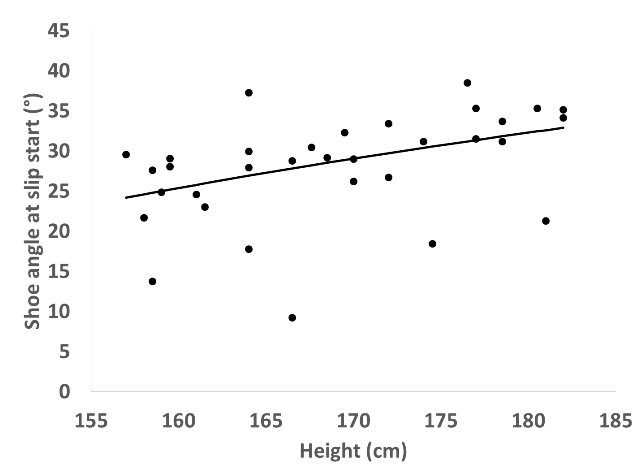

Figure 2: Influence of the subject's height on the shoe angle at slip-start.

4. Discussions

This study indicates that height influences under-shoe conditions (force and shoe angle) during slipping. Trends toward significance were also observed in force and shoe angle across the genders. However, it could not be determined whether these gender differences were due to differences in height across the groups or due to other gender-related factors. Previous studies have shown a connection between high foot-floor angles and an increased chance of experiencing a hazardous slip (Moyer, Chambers, Redfern, & Cham, 2006). Furthermore, high shoe angles have been associated with a reduced contact area and reduced friction due to hysteresis effects (Beschorner K. E., Redfern, Porter, & Debski, 2007) (Iraqi, Cham, Redfern, & Beschorner, 2018) (Moghaddam & Beschorner, 2017). Since height was positively correlated to shoe angle, this may indicate an increased risk of slipping for taller individuals. One countermeasure to improve friction at high shoe angles is beveling or curving the heel (Moghaddam & Beschorner, 2017). This countermeasure may be particularly important in large-sized shoes, which tend to be used by taller individuals.

The association between the two variables, force and shoe angle, and the individual's characteristic of height have implications for testing the COF of shoes worn over time by an individual. Testing the COF of shoes worn by an individual without accounting for the individual's characteristics may provide an inaccurate estimate of the slip risk for the individual. Complex interactions exist between footwear and force and between footwear and angle (Iraqi et al., 2018). Hence, when testing the COF of worn boots, controlling individual parameters could provide a more accurate estimate of that individual's slipping risk.

Certain limitations and future opportunities should be acknowledged. First, simple correlation analysis methods may not necessarily provide the most predictive equations. Multiple regression techniques (e.g., stepwise regression guided by cross-validation techniques) may provide improved predictions over the equations developed in this study. Furthermore, the methods were not intended to establish causality. If other studies sought to develop a causal relationship between height and under-shoe conditions, controlling for other parameters such as weight and gender would be necessary. Lastly, assessing this relationship across a wide range of footwear types would be needed to assess the generalizability of the results.

The finding that height plays an important role on under-shoe parameters that are known to affect COF values can guide devices to become more biofidelic. Future testing can then be performed to see if modifying test parameters to account for height differences for individualized tests more accurately predict slip outcomes.

5. Acknowledgements

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6. Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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