Required friction during overground walking is lower among obese compared to non-obese older men, but does not differ with obesity among women

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4 **Abstract**
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6 Obesity and aging have been independently associated with altered required friction
7 during walking, but it is unclear how these factors interact to influence the likelihood of
8 slipping. Therefore, the purpose of this study was to determine whether there are
9 differences related to obesity and aging on required friction during overground walking.
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11 Fourteen older non-obese, 11 older obese, 20 younger non-obese, and 20 younger obese
12 adults completed walking trials at both a self-selected and hurried speed. When walking
13 at a hurried speed, older obese men walked at a slower gait speed and exhibited lower
14 frictional demands compared both to older non-obese men and to younger obese men. No
15 differences in required friction were found between non-obese and obese younger adults.
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17 These results suggest that the increased rate of falls among obese or older adults is not
18 likely due to a higher risk of slip initiation.
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36 **Keywords:** required friction, obesity, aging
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1. Introduction

Slipping is responsible for a substantial proportion of occupational falls across many industry sectors, including 55% of falls among healthcare workers (Courtney et al., 2010), and 24% of falls among manufacturing plant workers (Amandus et al., 2012). In a specific example within the construction sector, slips caused 85% of falls to the floor and 30% of falls to a lower level during construction of the Denver International Airport between 1989 and 1994 (Lipscomb et al., 2006). Falls on the same level, many of which are caused by slips, are ranked as the second leading cause of disabling workplace injuries after overexertion—accounting for 16.4% of all workplace injuries and \$10.1 billion in direct costs (Liberty Mutual, 2015). A slip occurs when the required friction to prevent slipping at the shoe/floor interface exceeds the available friction. Required friction is dependent upon individual and gait characteristics (Anderson et al., 2014; Burnfield et al., 2005; Cooper et al., 2008; Moyer et al., 2006; Redfern et al., 2001), while available friction is dependent upon the tribology of shoe sole and supporting surface characteristics (Chang et al., 2014; Kim et al., 2013; Li et al., 2006; Tsai and Powers, 2009). The likelihood of slipping increases when either the required friction increases, or when the available friction decreases (Burnfield and Powers, 2006; Hanson et al., 1999; Tsai and Powers, 2009).

A growing number of studies suggest a higher rate of falling among individuals who are obese (Chau et al., 2004; Fjeldstad et al., 2008; Himes and Reynolds, 2012). This is problematic because obesity afflicts over 35% of adults in the United States (Ogden et al.,

2012). The higher rate of falling among individuals who are obese may be due, in part, to more slip-induced falls. There are two possible mechanisms by which obesity may result in more slip-induced falls, including a greater likelihood of slipping (i.e. propensity for slip initiation), or greater difficulty recovering balance once a slip is initiated (Allin et al., 2016). This study will focus on the former. Only two studies to our knowledge have investigated obesity-related differences in required friction while walking. Results of these studies were somewhat consistent in that both reported a higher required friction in a directional component of the overall required friction among obese or overweight younger adults. Wu et al (2012) reported a 40% higher required friction in the medial-lateral direction during overground walking among younger obese compared to healthy-weight men, but no difference in the overall (combined anterior-posterior and medial-lateral directions) required friction. Liu (2010) reported an 18% higher required friction in the anterior-posterior direction during treadmill walking among younger overweight compared to healthy-weight adults.

Advanced age is also associated with a higher rate of falling (Talbot et al., 2005), and may be due, in part, to a higher likelihood of slipping. Several studies have investigated differences between older and younger adults in required friction while walking, but with inconsistent results. Some have reported 13-21% lower required friction among older compared to younger adults (Anderson et al., 2014; Kim et al., 2005; Lockhart et al., 2007), while others have reported no age-related differences (Burnfield and Powers, 2003; Burnfield et al., 2005; Lockhart et al., 2005; Lockhart et al., 2003). It should also be noted, though, that older adults typically walk at slower speeds (Burnfield et al., 2005;

Kim et al., 2005; Lockhart et al., 2005; Lockhart et al., 2003) and/or with decreased step lengths (Lockhart et al., 2005; Lockhart et al., 2003), both of which decrease the required friction (Anderson et al., 2014; Burnfield et al., 2005; Cooper et al., 2008; Fendley and Medoff, 1996; Moyer et al., 2006).

Given the large obese and aging populations in the United States, the prevalence of slip-induced falls, and the potential for obesity and age to interactively influence slip-induced falls, the purpose of this study was to investigate obesity and age-related differences in the required friction while walking. We hypothesized that the required friction would be: 1) higher among obese compared to non-obese adults; 2) lower among older compared to younger adults; and 3) influenced by an obesity x age interaction, in that obesity-related differences would differ with age (or vice versa). The third hypothesis was based upon the possibility that the opposing effects of obesity and age described in the first two hypotheses would offset each other. Results from this study were intended to help clarify how obesity and age influence the likelihood of slipping while walking, as well as the higher rate of falls among these individuals. A better understanding of how individual factors such as obesity and age contribute to slip-induced falls can inform future fall prevention efforts.

2. Materials and Methods

Sixty-five adults completed this study (Table 1), including four groups of subjects: 14 older (age 60–80 years) non-obese (body mass index, or BMI 18-29.9 kg/m²) adults (6 women), 11 older obese (BMI 30-40 kg/m²) adults (5 women), 20 younger (age 18-30

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4 years) non-obese adults (10 women), and 20 younger obese adults (9 women). Subjects
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7 were screened to exclude those with self-reported musculoskeletal, neurological, or
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9 balance disorders that could influence their gait or safety. This study was approved by
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11 the local Institutional Review Board, and written consent was obtained from all subjects
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13 prior to participation.
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24 Subjects completed a single experimental session involving four walking trials at a self-
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26 selected speed and four walking trials at a “hurried” speed. Trials were completed along
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28 a 9-meter walkway covered in vinyl flooring. A hurried speed was investigated because
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30 required friction has been shown to increase with increasing gait speed (Anderson et al.,
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32 2014; Burnfield and Powers, 2003; Chang et al., 2014; Fendley and Medoff, 1996), and
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34 obesity/age differences may only exist at higher gait speeds. At no point during the
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36 experiment were subjects told there was a chance they would be slipped or perturbed in
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38 any way to elicit a fall. All subjects wore athletic clothing, and the same brand of athletic
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40 shoes in their requested size to avoid any differences in footwear between subject groups
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42 (Menant et al., 2009; Tsai and Powers, 2009). Walking trials at a self-selected speed were
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44 completed first. After a short rest, walking trials at the hurried speed were completed by
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46 instructing subjects to walk slightly faster than their self-selected speed. Gait speed was
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48 estimated after every trial by averaging the anterior-posterior speed of a reflective marker
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50 on the right scapula, and subjects were instructed to alter their speed depending on this
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52 measurement. The acceptable speed range for the hurried speed trials was 1.7-2.0 m/s.
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4 Some subjects could not reach this speed, in which case they were told to simply walk as
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6 fast as possible.
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11 During all trials, foot kinematics and ground reaction forces under the dominant
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13 (preferred to kick a ball) foot were collected. Foot kinematics were sampled at 100 Hz
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15 using a motion capture system (six MX T10 cameras, Vicon Motion Systems, Inc., Los
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17 Angeles, CA, USA) and reflective markers placed bilaterally on the heel, lateral
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19 malleolus, and fifth metatarsal head. Ground reaction were sampled at 1000 Hz using a
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21 force platform (Bertec Corporation, Columbus, OH) embedded in the walkway. Foot
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23 kinematics and ground reaction forces were respectively low-passed filtered at 5 and 40
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25 Hz (eighth-order, zero-phase-shift Butterworth filter), prior to further processing.
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33 Required friction was defined as the peak required coefficient of friction (RCOF) during
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35 the weight acceptance portion of the stance phase of gait (Anderson et al., 2014;
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37 Burnfield and Powers, 2006; Burnfield et al., 2005; Cham and Redfern, 2002; Redfern et
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39 al., 2001). RCOF throughout the stance phase was first determined by dividing the
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41 magnitude of the shear ground reaction force (resultant of the anterior-posterior and
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43 medial-lateral components) by the vertical ground reaction force (Anderson et al., 2014;
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45 Burnfield and Powers, 2006; Burnfield et al., 2005). The local peak in RCOF during
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47 weight acceptance was found when the anterior-posterior component of the ground
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49 reaction force was directed posteriorly (indicating the foot would tend to slip anteriorly),
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51 and when the vertical component of the ground reaction force was greater than 50 N.
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53 Using these criteria, spurious peaks in RCOF at the beginning and end of stance, that
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4 occur due to a small vertical ground reaction force, were ignored (Anderson et al., 2014;
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6 Burnfield and Powers, 2006; Burnfield et al., 2005). The peak RCOF used here typically
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8 occurred at 10-20% of stance time, although this range was not used as an explicit
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10 criterion to identify the peak. To better understand any differences in peak RCOF, we
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12 also determined the vertical and resultant shear ground reaction force at the time of peak
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14 RCOF during weight acceptance, and normalized these to body mass. Step length was
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16 determined as the anterior-posterior distance between heel markers on the left and right
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18 feet during consecutive stance phases.
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26 Separate three-way repeated measures analyses of covariance were used to investigate
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28 differences in peak RCOF, vertical GRF at peak RCOF, shear GRF at peak RCOF, and
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30 step length between obesity groups (non-obese or obese), age groups (older or younger),
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32 and self-reported sexual identity (women or men), with gait speed included as a
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34 covariate. Additionally, a three-way repeated measures analysis of variance was used to
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36 investigate differences in gait speed between obesity groups, age groups, and sex. In all
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38 analyses, a random effect for subject was included in the model to account for the four
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40 measurements made on each participant. Sexual identity was included as an independent
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42 variable given prior evidence of it influencing RCOF (Burnfield and Powers, 2003). All
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44 three-way and two-way interaction effects were initially included in these analyses.
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50 Iterative backwards elimination was then used to remove non-significant three-way and
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52 two-way interactions, until the final model included only main effects and significant
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54 interactions. In the event of a significant interaction, simple effects were investigated
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56 using contrasts. Self-selected speed trials and hurried speed trials were analyzed
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separately because the effects of gait speed on our dependent variables have been established (Anderson et al., 2014; Fendley and Medoff, 1996), and thus were not a focus here. With the exception of peak RCOF, analyses were performed on ranks due to substantial violation of parametric model assumptions (i.e., non-normal distributions of residuals). All statistical analyses were conducted using JMP Pro 11 (Cary, North Carolina, USA) with a significance level of $\alpha = 0.05$. For post-hoc tests of higher-order interactions, Bonferroni corrections were applied (12 comparisons; $\alpha = 0.004$). Summary values are reported as means $\pm$ standard deviation

3. Results

3.1 Self-Selected Speed Trials

Self-selected gait speed was 1.30 ± 0.17 m/s across all subjects, and did not differ between obesity groups ($p=0.064$), age groups ($p=0.427$), or by sex ($p=0.679$). Step length did not differ between obesity groups ($p = 0.977$), was 0.4% shorter among the older group ($p=0.019$), 6.1% shorter among women ($p<0.001$), and increased with gait speed ($p<0.001$).

Peak RCOF and ground reaction force measures (Table 2) did not exhibit any interaction effects involving obesity group, age group, or sex. Peak RCOF did not differ between obesity groups ($p = 0.242$), was 5.9% lower among the older group ($p=0.010$), did not differ by sex ($p=0.487$), and increased as gait speed increased ($p<0.001$). The vertical ground reaction force at peak RCOF did not differ between obesity groups ($p = 0.609$), was 22.6% higher among the older group ($p=0.005$), did not differ by sex ($p=0.738$), and

increased with gait speed ($p=0.045$). The shear ground reaction force at peak RCOF did not differ between obesity groups ($p = 0.609$), age groups ($p=0.094$), or by sex ($p=0.529$), but increased with gait speed ($p<0.001$).

Insert Table 2 about here

3.2 Hurried Speed Trials

Gait speed was 1.90 ± 0.13 m/s across all subjects. Two older obese subjects could not achieve the 1.7-2.0 m/s desired gait speed during any of their four hurried speed trials. Six subjects achieved the desired gait speed for some, but not all, of their hurried speed trials (one younger obese, one older non-obese, and four older obese). Importantly, gait speed was higher during hurried trials, compared to self-selected trials, within each age/obesity group ($p<0.001$). Gait speed among hurried gait speed trials exhibited an obesity group $\times$ age group $\times$ sex interaction (Figure 1, $p=0.025$). Gait speed was 15.0% slower among older obese men (1.70 ± 0.04 m/s) compared to older non-obese men (2.01 ± 0.03 m/s; $p<0.001$). Gait speed was also 10.6% slower among older obese men (1.77 ± 0.14 m/s) compared to younger obese men (1.91 ± 0.03 m/s; $p<0.001$). Step length did not exhibit any interaction effects, and was 5.6% shorter among the obese group ($p=0.024$), 7.5% shorter among the older group ($p<0.001$), 9.6% shorter among women ($p<0.001$), and increased with gait speed ($p<0.001$).

Insert Figure 1 about here

Peak RCOF during weight acceptance (Table 3) exhibited an obesity group $\times$ age group $\times$ sex interaction (Figure 2, $p=0.027$). One obesity-related simple effect was found in that peak RCOF was 17.3% lower among older obese men (0.218 ± 0.024) compared to older non-obese men (0.263 ± 0.040 ; $p=0.002$). Two age-related simple effects were found, with peak RCOF was 17.9% lower among older obese men compared to younger obese men (0.265 ± 0.031 ; $p<0.001$), and 17.5% lower among older non-obese women (0.218 ± 0.043) compared to younger non-obese women (0.264 ± 0.023 ; $p=0.004$). One sex-related simple effect was found, in that peak RCOF was 17.4% lower among older non-obese women compared to older non-obese men (0.264 ± 0.040 ; $p=0.004$). The vertical ground reaction force at peak RCOF (Table 3) was 4.9% higher among the obese group ($p = 0.012$), 15.1% higher among the older group ($p=0.001$), did not differ by sex ($p=0.933$), and increased with gait speed ($p<0.001$). The shear ground reaction force at peak RCOF (Table 3) did not differ between obesity groups ($p = 0.569$), age groups ($p=0.679$), or by sex ($p=0.181$), but increased with gait speed ($p=0.019$).

Insert Figure 2 about here

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4. Discussion

The purpose of this study was to investigate obesity and age-related differences in the required friction while walking. We hypothesized that the required friction would be higher among obese compared to non-obese adults. This hypothesis was not supported because peak RCOF was *lower* among obese older men compared to non-obese older

men when walking at a hurried speed. No obesity-related differences were found while walking at a slower self-selected speed. Our second hypothesis was that the required friction would be lower among older compared to younger adults. This hypothesis was supported because peak RCOF was lower among older adults compared to younger adults when walking at a self-selected speed, and lower among older obese men compared to younger obese men when walking at a hurried speed. Our third hypothesis was that the required friction would be influenced by an obesity x age interaction. This hypothesis was supported in that, among older adults, peak RCOF was *lower* among obese men compared to non-obese men when walking at a hurried speed, while no obesity-related differences were found among younger adults. Although some subjects were unable to achieve the targeted 1.7-2.0 m/s speed during some or all of their hurried trials, this did not have an adverse effect on our main findings. The hurried speed, even if not within the specific range for all trials, still represented the situation when walking faster than at a self-selected speed. Moreover, the use of gait speed as a covariate in our statistical analysis accounted for the modest differences in mean hurried gait speed between four age/obesity groups. Overall, these results suggest that individuals who are obese are not more likely to experience the initiation of a slip at weight acceptance while walking. However, they may still suffer from a higher rate of slip-induced falls due to a greater difficulty recovering balance after a slip has initiated (Allin et al., 2016).

Unlike the present study, two prior studies provide evidence for a higher required friction among individuals who are obese. Wu et al. (2012) compared peak RCOF between younger obese and healthy-weight adults (total $n = 10$) during overground walking at a

self-selected speed. Their results showed no obesity-related differences in peak RCOF when using the resultant shear ground reaction force, but a higher peak RCOF among obese adults when only using the medial-lateral component of the shear ground reaction force (not investigated here). Two differences between Wu et al. (2012) and the present study are notable when interpreting these results. First, Wu et al. (2012) only studied younger men walking at a self-selected speed, while the present study investigated younger and older men and women walking at both self-selected and hurried speeds (peak RCOF differences in the present study were only found during the hurried speed). Second, Wu et al. (2012) instructed their subjects to have consecutive foot strikes on two separate force platforms embedded in their laboratory. Constraining step length in this manner may have artificially influenced peak RCOF (Burnfield and Powers, 2003; Cooper et al., 2008). In the second study, Liu (2010) compared peak RCOF between younger overweight and healthy-weight adults (total $n = 12$) while walking on a split-belt treadmill at a self-selected speed. Their results showed higher peak RCOF among overweight adults only for the anterior-posterior component of the shear ground reaction force (not investigated here). Notable differences between Liu (2010) and the present study again include differences in subject characteristics (healthy-weight compared to overweight), walking speeds (self-selected speed not reported), and the use of a split-belt treadmill. Known differences between overground and treadmill walking (Lee and Hidler, 2008; Riley et al., 2007; Stolze et al., 1997) may have contributed to the differences their results and the present study. In light of the differences in results between these prior studies and our, we believe the current results may be more robust, by including a larger, more diverse subject group, by having subjects walk naturally

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4 overground at two different speeds, and by investigating the total peak RCOF as it
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6 actually exists at the shoe-floor interface rather than its individual directional
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8 components.
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14 A novel finding from the present study was that peak RCOF was lower among older
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16 obese men when compared to older non-obese men when walking at a hurried speed.
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18 Additionally, step length was shorter among obese adults, and the vertical GRF
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20 (normalized to body mass) at peak RCOF was higher among obese adults. Because peak
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22 RCOF is determined from the ratio of resultant shear GRF to vertical GRF, and resultant
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24 shear GRF was not influenced by obesity, age, or sex, an increase in vertical GRF at peak
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26 RCOF would result in a lower RCOF value. Additionally, reductions in RCOF have also
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28 been associated with decreases in step length (Cham and Redfern, 2002; Cooper et al.,
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30 2008). Combined, these results suggest that older obese men walk at a hurried speed
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32 with a lower peak RCOF primarily due to taking shorter steps, and a higher vertical GRF,
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34 when compared to older non-obese men.
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43 Prior studies have reported 13-21% lower peak RCOF among older adults compared to
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45 younger adults while walking at a self-selected speed (Anderson et al., 2014; Kim et al.,
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47 2005; Lockhart et al., 2007). The present study expands upon these prior studies by
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49 identifying similar age-related differences during self-selected gait in a subject group
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51 that, unlike these prior studies, included both obese and non-obese men and women, and
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53 by identifying similar age-related differences during hurried gait among obese men and
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55 non-obese women. While walking at a self-selected speed, peak RCOF was 5.9% lower
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4 among older obese and non-obese men and women when compared to younger obese and
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6 non-obese men and women. It was not immediately clear why the self-selected gait
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8 speed did not differ between age groups, although others have reported similar findings
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10 (Anderson et al., 2014; Kang and Dingwell, 2008). Two potential reasons include older
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12 adults who walked faster than expected (six of the fastest ten trials were by older adults),
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14 or young adults who walked slower than expected (nine of the slowest ten were by young
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16 adults). While walking at a hurried speed, peak RCOF was 17-18% lower among older
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18 obese men and non-obese women when compared to younger obese men and non-obese
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20 women. These differences in peak RCOF may have resulted, in general and in part, from
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22 main effects of age on vertical GRF (15-23% higher among older adults) and step length
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24 (0.4-7.5% shorter among older adults). Although gait speed was slower among older
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26 obese men compared to young obese men while walking at a hurried speed, our statistical
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28 analysis included gait speed as a covariate, thereby accounting for this difference in gait
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30 speed when identifying age-related differences in peak RCOF between these same to
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32 subject sub-groups. Anderson et al. (2014) found gait speed and step length to have
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34 independent and opposite effects on the required friction while walking. In particular, an
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36 increase in step length (without any change in speed) was associated with an increase in
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38 peak RCOF, while an increase in gait speed (without any change in step length) was
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40 associated with a decrease in peak RCOF. Similarly, Cooper et al. (2008) also found peak
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42 RCOF to increase as step length increased.
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55 Among older non-obese adults walking at a hurried speed, women exhibited a lower peak
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57 RCOF compared to men. These results are consistent with Burnfield and Powers (2003),
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4 who reported a lower required friction among women compared to men at a fast walking
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6 speed (~2.2 m/s). However, the direction of this difference reversed at a slower speed
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8 (0.95 m/s) when the required friction was higher among women than men. Rozin Kleiner
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10 et al. (2015) also reported a higher required friction among women aged 40 – 70 years
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12 compared to men during barefoot walking at a self-selected speed. Differences in
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14 footwear (barefoot compared to shod), gait speed (not reported), and step length (not
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16 reported) may have contributed to the inconsistent sex-related differences between this
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18 prior study and the present study. For example, barefoot walking has been shown to
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20 exhibit lower peak shear GRF, and higher first peak of vertical GRF at heel contact,
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22 compared to shod walking (Cooper et al., 2008; Sacco et al., 2010). Additionally, women
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24 tend to walk with shorter step lengths (Laufer, 2003), and shorter step lengths are
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26 associated with reductions in RCOF (Anderson et al., 2014; Cooper et al., 2008).
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36 Two limitations warrant discussion. First, this study was limited to healthy adults
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38 walking on a level surface, and may not generalize to other conditions or populations.
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40 Second, as is with all cross-sectional studies, there could be other differences between
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42 groups that contribute to the differences found, and these differences do not necessarily
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44 imply causation.
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50 **5. Conclusions**

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52 Older obese men exhibited lower shoe/frictional demands compared to older non-obese
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54 men when walking at a hurried speed. No obesity-related differences were found in
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56 shoe/floor frictional demand when walking at a self-selected speed. These results suggest
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4 that the higher rate of falls among individuals who are obese that is reported elsewhere is
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7 not due to a greater likelihood of a slip initiating at heel strike while walking. The
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9 present work also expands upon prior studies by identifying similar age-related
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11 differences in shoe/floor frictional demands among a subject group that included obese
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13 and non-obese men and women.
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19 **Conflicts of Interest:** The authors report no conflict of interest.
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Figure Captions

Figure 1. Arithmetic means (and standard deviations) of gait speed during hurried speed trials, for which there was a significant obesity group x age group x sex interaction.

Statistical significance ($p<0.004$) is indicated by an “o” for an obesity-related simple effect, an “a” for an age-related simple effect, and a “s” for a sex-related simple effect.

Figure 2. Arithmetic means (and standard deviations) of peak RCOF during hurried speed trials, for which there was a significant obesity group x age group x sex interaction.

Statistical significance ($p<0.004$) is indicated by an “o” for an obesity-related simple effect, an “a” for an age-related simple effect, and a “s” for a sex-related simple effect.

References

Allin, L.J., Wu, X., Nussbaum, M.A., Madigan, M.L., 2016. Falls resulting from a laboratory-induced slip occur at a higher rate among individuals who are obese. *Journal of Biomechanics* 49, 678-683.

Amandus, H., Bell, J., Tiesman, H., Biddle, E., 2012. The epidemiology of slips, trips, and falls in a helicopter manufacturing plant. *Hum Factors* 54, 387-395.

Anderson, D.E., Franck, C.T., Madigan, M.L., 2014. Age differences in the required coefficient of friction during level walking do not exist when experimentally-controlling speed and step length. *J Appl Biomech* 30, 542-546.

Burnfield, J.M., Powers, C.M., 2003. Influence of age and gender on utilized coefficient of friction during walking at different speeds, in: Marpet, M., Sapienza, M. (Eds.), *Metrology of pedestrian locomotion and slip resistance*. ASTM International, West Conshohocken, PA, pp. 3-16.

Burnfield, J.M., Powers, C.M., 2006. Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. *Ergonomics* 49, 982-995.

Burnfield, J.M., Tsai, Y.J., Powers, C.M., 2005. Comparison of utilized coefficient of friction during different walking tasks in persons with and without a disability. *Gait Posture* 22, 82-88.

Cham, R., Redfern, M.S., 2002. Changes in gait when anticipating slippery floors. *Gait Posture* 15, 159-171.

Chang, W.-R., Matz, S., Chang, C.-C., 2014. The stochastic distribution of available coefficient of friction for human locomotion of five different floor surfaces. *Applied Ergonomics* 45, 811-815.

Chau, N., Gauchard, G.C., Siegfried, C., Benamghar, L., Dangelzer, J.L., Francais, M., Jacquin, R., Sourdot, A., Perrin, P.P., Mur, J.M., 2004. Relationships of job, age, and life conditions with the causes and severity of occupational injuries in construction workers. *Int Arch Occup Environ Health* 77, 60-66.

Cooper, R.C., Prebeau-Menezes, L.M., Butcher, M.T., Bertram, J.E.A., 2008. Step length and required friction in walking. *Gait & Posture* 27, 547-551.

Courtney, T.K., Lombardi, D.A., Sorock, G.S., Wellman, H.M., Verma, S., Brennan, M.J., Collins, J., Bell, J., Chang, W.R., Grnqvist, R., Wolf, L., DeMaster, E., Matz, M., 2010. Circumstances of slips trips and falls among Hospital workers. *Injury Prevention* 16, A173-A174.

Fendley, A., Medoff, H., 1996. Required Coefficient of Friction Versus Top-Piece/Outsole Hardness and Walking Speed: Significance of Correlations.

Fjeldstad, C., Fjeldstad, A.S., Acree, L.S., Nickel, K.J., Gardner, A.W., 2008. The influence of obesity on falls and quality of life. *Dyn Med* 7, 4.

Hanson, J.P., Redfern, M.S., Mazumdar, M., 1999. Predicting slips and falls considering required and available friction. *Ergonomics* 42, 1619-1633.

Himes, C.L., Reynolds, S.L., 2012. Effect of obesity on falls, injury, and disability. *J Am Geriatr Soc* 60, 124-129.

Kang, H.G., Dingwell, J.B., 2008. Separating the effects of age and walking speed on gait variability. *Gait Posture* 27, 572-577.

Kim, I.J., Hsiao, H., Simeonov, P., 2013. Functional levels of floor surface roughness for the prevention of slips and falls: clean-and-dry and soapsuds-covered wet surfaces. *Appl Ergon* 44, 58-64.

1
2
3
4 Kim, S., Lockhart, T., Yoon, H.Y., 2005. Relationship between age-related gait adaptations and
5
6 required coefficient of friction. *Safety science* 43, 425-436.
7
8
9
10 Laufer, Y., 2003. Age- and gender-related changes in the temporal-spatial characteristics of
11
12 forwards and backwards gaits. *PRI Physiotherapy Research International* 8, 131-142.
13
14
15 Lee, S.J., Hidler, J., 2008. Biomechanics of overground vs. treadmill walking in healthy
16
17 individuals. *Journal of applied physiology* (Bethesda, Md. : 1985) 104, 747-755.
18
19
20 Li, K.W., Wu, H.H., Lin, Y.C., 2006. The effect of shoe sole tread groove depth on the friction
21
22 coefficient with different tread groove widths, floors and contaminants. *Appl Ergon* 37, 743-748.
23
24
25
26 Liberty Mutual, R.I.f.S., 2015. 2014 Liberty Mutual Workplace Safety Index.
27
28
29
30 Lipscomb, H.J., Glazner, J.E., Bondy, J., Guarini, K., Lezotte, D., 2006. Injuries from slips and
31
32 trips in construction. *Appl Ergon* 37, 267-274.
33
34
35
36 Liu, J., 2010. Effect of excessive adiposity on risk of slip initiation and postural stability,
37
38 International Conference on Fall Prevention and Protection, Morgantown, WV.
39
40
41 Lockhart, T.E., Smith, J.L., Woldstad, J.C., 2005. Effects of aging on the biomechanics of slips
42
43 and falls. *Hum Factors* 47, 708-729.
44
45
46
47 Lockhart, T.E., Spaulding, J.M., Park, S.H., 2007. Age-related slip avoidance strategy while
48
49 walking over a known slippery floor surface. *Gait & Posture* 26, 142-149.
50
51
52 Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of age-related gait changes on the
53
54 biomechanics of slips and falls. *Ergonomics* 46, 1136-1160.
55
56
57
58
59
60
61
62
63
64
65

Menant, J.C., Steele, J.R., Menz, H.B., Munro, B.J., Lord, S.R., 2009. Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. *Gait & Posture* 29, 392-397.

Moyer, B.E., Chambers, A.J., Redfern, M.S., Cham, R., 2006. Gait parameters as predictors of slip severity in younger and older adults. *Ergonomics* 49, 329-343.

Ogden, C.L., Carroll, M.D., Kit, B.K., Flegal, K.M., 2012. Prevalence of obesity in the United States, 2009-2010. *NCHS Data Brief*, 1-8.

Redfern, M.S., Cham, R., Gielo-Perczak, K., Grönqvist, R., Hirvonen, M., Lanshammar, H., Marpet, M., Pai, C.Y.-C., Powers, C., 2001. Biomechanics of slips. *Ergonomics* 44, 1138 - 1166.

Riley, P.O., Paolini, G., Della Croce, U., Paylo, K.W., Kerrigan, D.C., 2007. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait Posture* 26, 17-24.

Rozin Kleiner, A.F., Galli, M., Araujo do Carmo, A., Barros, R.M., 2015. Effects of flooring on required coefficient of friction: Elderly adult vs. middle-aged adult barefoot gait. *Appl Ergon* 50, 147-152.

Sacco, I.C., Akashi, P.M., Hennig, E.M., 2010. A comparison of lower limb EMG and ground reaction forces between barefoot and shod gait in participants with diabetic neuropathic and healthy controls. *BMC musculoskeletal disorders* 11, 1-9.

Stolze, H., Kuhtz-Buschbeck, J.P., Mondwurf, C., Boczek-Funcke, A., Jöhnk, K., Deuschl, G., Illert, M., 1997. Gait analysis during treadmill and overground locomotion in children and adults. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control* 105, 490-497.

1
2
3
4 Talbot, L.A., Musiol, R.J., Witham, E.K., Metter, E.J., 2005. Falls in young, middle-aged and
5
6 older community dwelling adults: perceived cause, environmental factors and injury. BMC Public
7
8 Health 5, 86.
9

10
11
12 Tsai, Y.-J., Powers, C.M., 2009. Increased shoe sole hardness results in compensatory changes in
13
14 the utilized coefficient of friction during walking. Gait & Posture 30, 303-306.
15

16
17
18 Wu, X., Lockhart, T.E., Yeoh, H.T., 2012. Effects of obesity on slip-induced fall risks among
19
20 young male adults. J Biomech 45, 1042-1047.
21
22
23
24
25
26
27
28
29
30
31
32
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Figure 1

Figure 2

Table 1. Subject Characteristics (mean ± standard deviation)

	N	Men	Women	Age (yrs)	Height (cm)	Mass (kg)	BMI (kg/m ²)
Older Non-Obese	14	6	8	66.6 ± 4.9	171.8 ± 14.1	72.0 ± 13.8	24.2 ± 1.7
Older Obese	11	6	5	70.5 ± 7.4	170.2 ± 12.0	93.5 ± 12.3	32.2 ± 2.0
Younger Non-Obese	20	10	10	24.5 ± 3.5	171.3 ± 6.8	65.3 ± 7.5	22.3 ± 2.3
Younger Obese	20	11	9	23.5 ± 3.2	172.2 ± 8.7	99.1 ± 13.9	33.4 ± 3.4

Table 2. Arithmetic means (and standard deviations) of gait characteristics, RCOF, and GRF during self-selected walking.

	Obesity		Age		Sex	
	Non-Obese	Obese	Younger	Older	Men	Women
Gait Speed (m/s)	1.35 ± 0.18	1.25 ± 0.15	1.28 ± 0.17	1.33 ± 0.17	1.31 ± 0.17	1.30 ± 0.18
Step Length (m) ^{asg}	0.684 ± 0.058	0.661 ± 0.058	0.674 ± 0.056	0.672 ± 0.064	0.694 ± 0.058	0.651 ± 0.052
peak RCOF ^{ag}	0.220 ± 0.032	0.220 ± 0.027	0.226 ± 0.027	0.212 ± 0.032	0.219 ± 0.032	0.222 ± 0.027
Vertical GRF at peak RCOF (N/kg) ^{ag}	7.51 ± 2.57	7.27 ± 2.17	6.78 ± 2.27	8.31 ± 2.26	7.38 ± 2.40	7.42 ± 2.39
Shear GRF at peak RCOF (N/kg) ^g	1.66 ± 0.64	1.59 ± 0.47	1.52 ± 0.54	1.77 ± 0.57	1.61 ± 0.57	1.64 ± 0.56

Superscripts indicate a main effect of obesity^o, age^a, sex^s, and gait speed^g ($p < 0.05$).

Table 3. Arithmetic means (and standard deviations) of gait characteristics, RCOF, and GRF during hurried walking.

	Obesity		Age		Sex	
	Non-Obese	Obese	Younger	Older	Men	Women
Gait Speed (m/s) [*]	1.96 ± 0.11	1.84 ± 0.13	1.91 ± 0.10	1.89 ± 0.17	1.91 ± 0.14	1.89 ± 0.13
Step Length (m) ^{oasg}	0.826 ± 0.083	0.782 ± 0.076	0.831 ± 0.072	0.768 ± 0.084	0.844 ± 0.081	0.763 ± 0.061
peak RCOF [*]	0.256 ± 0.038	0.241 ± 0.034	0.260 ± 0.027	0.232 ± 0.042	0.258 ± 0.035	0.240 ± 0.036
Vertical GRF at peak RCOF (N/kg) ^{oag}	10.51 ± 2.55	11.03 ± 2.31	10.14 ± 2.35	11.67 ± 2.33	10.93 ± 2.44	10.55 ± 2.46
Shear GRF at peak RCOF (N/kg) ^{*g}	2.70 ± 0.83	2.64 ± 0.61	2.64 ± 0.66	2.74 ± 0.85	2.82 ± 0.76	2.52 ± 0.68

Superscripts indicate a main effect of obesity^o, age^a, sex^s, and gait speed^g ($p < 0.05$). A three-way interactive effect of BMI, age, and sex is indicated by a superscript ^{*} ($p < 0.05$).