A pilot study exploring obesity-related differences in fall rate and kinematic response resulting from a laboratory-induced trip

OCCUPATIONAL APPLICATIONS

A higher percentage of young adults with a higher body mass index (BMI) fell after a laboratory-induced trip compared to young adults with a lower BMI, although this difference did not reach statistical significance. Young adults with a higher BMI also exhibited a kinematic response to the trip that was less favorable than adults with a lower BMI. This study provides preliminary evidence that obesity may increase the risk of falls after tripping among young obese workers, and that this increased risk may be due to a less favorable balance recovery response after tripping. Additional larger-scale studies are needed to better understand contributing and modifiable factors that can be targeted via intervention or other fall prevention strategies.

TECHNICAL ABSTRACT

Background: Obese adults are reported to fall at a higher rate than non-obese adults. **Purpose:** To help determine the reason for this higher fall rate, we quantified fall rates, kinematics at trip onset, and kinematics during the response to a laboratory-induced trip among two groups of young adults with higher and lower body mass indexes (BMI) that approximated obese and healthy-weight ranges. Our focus was on young adults given that they comprise a substantial portion of the workforce. **Methods:** Twenty-one young adult subjects, including 10 with a lower BMI (BMI 19.4-25.7 kg/m^2) and 11 with a higher BMI (BMI 29.8-42.9 kg/m^2), walked along a 10 m walkway at a purposeful speed. During a randomly selected walking trial, an obstacle was raised to elicit a trip. **Results:** Among the 19 subjects who unambiguously fell or recovered, 30% of subjects with higher body mass index (BMI) fell and 0% of lower-BMI subjects fell, but this difference did not reach statistical significance. Among the 15 subjects who used an elevating strategy, all recovered balance, and the only kinematic response variable that differed between BMI groups was that recovery step time was longer among the higher-BMI group. Among the four subjects who used a lowering strategy, no statistical analysis was possible due to a small number of subjects, but several measures were consistent with a less favorable kinematic response among the three higher-BMI fallers compared to the one lower-BMI subject who recovered. **Conclusions:** This study provides preliminary evidence that obesity may adversely influence fall rate and recovery kinematics after tripping among young adults. Additional larger-scale studies are needed to better understand contributing and modifiable factors that can be targeted via intervention.

Keywords: gait; falls; trip recovery; obesity

1. INTRODUCTION

Occupational slips, trips, and falls continue to be substantial economic and societal issues (Kemmlert et al., 2001; Layne et al., 2004; Leamon et al., 1995). These accidents account for more than 700 deaths and 200,000 injuries involving days away from work each year, along with annual direct costs exceeding $11 billion (Liberty Mutual Research Institute for Safety, 2007b). Labor force demographics in the U.S. have changed significantly over the past few decades in that the prevalence of obesity among all workers has increased from 23.5% in 2004 to 27.6% in 2011 (Gu et al., 2014). This is problematic because individuals who are obese have a higher rate of falling (Fjeldstad et al., 2008; Himes et al., 2012; Patino et al., 2010) and higher fall-related injuries in occupational settings (Ambrose et al., 2013; Janssen et al., 2011; Kemmlert et al., 2001; Swaen et al., 2014).

The higher rate of falling and fall-related injuries among individuals who are obese may be due, to some extent, to a higher number of trip-induced falls. Trip-induced falls account for a sizable proportion of workplace falls including 23% of falls among construction workers (Lipscomb et al., 2006), and 32% of falls among manufacturing workers (Amandus et al., 2012) and healthcare workers (Liberty Mutual Research Institute for Safety, 2007a). Tripping occurs when foot motion during the swing phase of gait is impeded by an obstacle, and results in forward rotation of the body/trunk about the stance foot. Averting a fall after tripping has, in essence, two requisites: 1) arrest the forward rotation of the body/trunk (Grabiner et al., 2008; Grabiner et al., 1993; Pijnappels et al., 2005b; van Dieen et al., 2005), and 2) maintain adequate hip height to allow subsequent stepping (Pavol et al., 2001; Pijnappels et al., 2005b). A stepping response is commonly attempted to achieve these requisites. Trips during early swing typically elicit an elevating stepping strategy in which the swing foot that contacts the tripping obstacle is immediately lifted over the obstacle in an attempt to complete a recovery step over the obstacle (Eng et al., 1994; Pijnappels et al., 2004). Trips during late swing typically elicit a lowering stepping strategy in which the swing foot that contacts the tripping obstacle is immediately lowered to the ground on the near side of the obstacle, then the contralateral foot is used to attempt a recovery step over the obstacle (Eng et al., 1994). Trips during mid-swing can elicit either elevating and lowering strategies (Schillings et al., 2000). The stepping response attempts to extend the base of support anteriorly so the subsequent stance phase provides a ground reaction force that can help decelerate the body/trunk forward rotation about the stance foot (Pavol et al., 2001). After completing a recovery step over the obstacle, it is also important to prevent buckling of the stepping limb to maintain adequate hip height to allow subsequent stepping (Madigan et al., 2005; Pavol et al., 2001). Along with the stepping response, a push-off/extension response in the stance limb (the limb not performing the recovery step over the obstacle) also contributes to trunk deceleration and helps maintain adequate hip height (Pijnappels et al., 2004, 2005a). The importance and effectiveness of these stepping and push-off responses are reflected in differences between falls and successful recoveries after tripping. Falls after laboratory-induced trips or simulated trips have been associated with altered body kinematics at trip onset (Pavol et al., 2001), longer times to lower the tripped foot to the ground when using a lowering strategy (Pavol et al., 2001), shorter recovery steps (Crenshaw et al., 2012; Owings et al., 2001; Pavol et al., 2001; van Dieen et al., 2005), longer times to complete the recovery step (Crenshaw et al., 2012; Owings et al., 2001), less anterior placement of the stepping foot relative to the center of mass/pelvis at foot strike of the first recovery step over the obstacle (Crenshaw et al., 2012; Owings et al., 2001; Pijnappels et al., 2005b), larger trunk angle and trunk angular velocity at foot strike of the first recovery step over the obstacle (Crenshaw et al., 2012; Grabiner et al., 2008; Owings et al., 2001; Pavol et al., 2001), and a lower hip height at foot strike of the first recovery step over the obstacle (Pavol et al., 2001; Pijnappels et al., 2005b).

The effect of obesity on trip-induced falls has received little attention, however. The only study to our knowledge that has investigated obesity and trip-induced falls reported a 46% fall rate after a laboratory-induced trip among obese females of age 55 and older compared to a 25% fall rate among those who were not obese, although this difference did not reach statistical significance (Rosenblatt et al., 2012). Obesity-related differences in the kinematic/stepping response to these trips were not investigated, but could provide insight on the underlying reasons for the apparently higher fall rate among obese participants, and yield valuable guidance toward the development of strategies to reduce the occurrence of trip-induced falls among individuals who are obese. Therefore, the purpose of this study was to explore obesity-related differences in 1) fall rate resulting from a laboratory-induced trip, 2) kinematics at trip onset, and 3) kinematics during the balance recovery response. We studied young adults because they comprise a large proportion of the U.S. workforce (36% were age 16-34 in 2014) (BLS, 2015), and because obesity may influence their risk of trip-induced falls differently than adults age 55 and older studied earlier (Rosenblatt et al., 2012). As such, trip-induced fall prevention strategies for obese workers may need to differ between young and older adults. We hypothesized that subjects with a higher BMI would exhibit a higher fall rate, less favorable kinematics at trip onset, and a less favorable kinematic response compared to subjects with a lower BMI. 'Less favorable' kinematics indicates similarities with trip-induced falls described above. The results from this study were intended to help better understand the contribution of obesity to trip-induced falls among young workers, and to facilitate planning of subsequent larger-scale projects aimed at understanding factors and underlying biomechanical mechanisms contributing to falls in the workplace.

2. METHODS

Twenty-one young adults completed the study and were used to form two groups with respect to body mass index (BMI): 10 with a lower BMI (BMI mean ± SD 23.4 ± 2.0 kg/m^2; BMI range 19.4-25.7 kg/m^2; mass 65.9 ± 9.8 kg; stature 1.7 ± 0.1 m; age 26.1 ± 3.0 years; six females), and 11 with a higher BMI (BMI 34.1 ± 4.6 kg/m^2; BMI range 29.8-42.9 kg/m^2; mass 100.2 ± 11.4 kg; stature 1.7 ± 0.1 m; age 23.5 ± 2.9 years; five females). Exclusion criteria including any self-reported musculoskeletal, neurological, or balance disorders that affected gait, and a change in body mass greater than 2.3 kg over the prior six months. The study was approved by the university Institutional Review Board, and all subjects provided written informed consent prior to participation.

All testing was performed in a single experimental session. Subjects were given a verbal overview of the protocol, and informed there was a chance they would be tripped or slipped to elicit a fall (although no attempt was made to cause the subjects to slip). Subjects then donned standardized athletic clothes and shoes, and a full-body safety harness to prevent impact of the knees or hands with the ground in the event of an unsuccessful trip recovery. The safety harness was attached to an overhead track using a harness spreader bar, and the length of the spreader bar was adjusted such that the subject's knees (when flexed 90 degrees) were approximately 5 cm from the floor when allowing the harness to fully support body weight. Ten practice gait trials were performed along a 10 m walkway to allow subjects to become accustomed to the experimental setup and procedures. Subjects were given a starting position near one end of the walkway, and asked to walk at a purposeful speed with their eyes focused straight ahead. After completing the practice trials, subjects donned wireless headphones and watched a television program on computer monitors positioned at both ends of the walkway to divert attention from tripping. A message on the screen instructed the subject when to turn around and walk to the far end of the walkway while continuing to watch the television program on the monitor positioned at the far end of the walkway. The starting position on the walkway was varied, and trials were repeated until the dominant foot was naturally and consistently positioned approximately 4 cm prior to the concealed tripping obstacle near the middle of the walkway. During a randomly selected trial, and upon this same foot placement relative to the obstacle, the trip obstacle was manually activated by pulling a concealed rope to raise the 7-cm-high obstacle and elicit a trip. All subjects were successfully tripped on their first and only attempt to be tripped.

During all tripping trials, ground reaction forces were sampled at 1000 Hz from a 0.9 × 0.9 m force platform (Bertec Corporation, Columbus, OH) integrated into the walkway immediately after (or, forward in the direction of gait progression) the tripping obstacle, and harness load was sampled at 1000 Hz using a uni-axial load cell (Cooper Instruments and Systems, Warrenton, VA). Both signals were low-pass filtered at 20 Hz (eighth-order zero-phase-shift Butterworth filter) using Matlab 2013a (The Mathworks Inc., Natick, MA). Body position was sampled at 100 Hz using a modified Helen Hayes marker set and a six-camera motion capture system (MX-T10, Vicon Motion Systems Inc., Los Angeles, CA), and subsequently low-pass filtered at 6 Hz (8th-order, zero-phase-shift Butterworth filter).

Similar to prior work (Brady et al., 2000), harness load was used to classify trip recovery outcome as: 1) a recovery when peak harness force was less than 30% of subject body weight, 2) harness-assist when peak force was 30-50% of subject body weight, and 3) a fall when peak force exceeded 50% of body weight. Outcomes for one higher-BMI subject and one lower-BMI subject were deemed harness-assisted, and were removed from further analysis to avoid trials with an ambiguous outcome had the subject not been wearing the harness.

Body kinematics at trip onset, identified by a transient spike in acceleration of a foot marker on the head of the fifth metatarsal, were quantified using four variables. *Gait speed* was the mean anterior-posterior speed of a marker on the right scapula during the trip trial up to trip onset. The *phase of gait at trip onset* was determined from the anterior-posterior distance between markers on the right and left lateral malleoli, and expressed as a percentage of the length of the contralateral stride prior to the trip (Pavol et al., 2001). *Trunk angle and angular velocity* in the sagittal plane at trip onset were calculated using the angle between vertical and a line passing through markers on the right greater trochanter and the right acromion, and trunk angle was considered to be 0 degrees during upright quiet standing (increasing when flexing forward). Trunk angular velocity was calculated using trunk angle and a finite difference method.

The kinematic response was quantified using seven measures. *Time to lower foot to floor* (only when using a lowering strategy) was defined as the time between trip onset and the tripped foot being immediately lowered to the floor. The time the foot was lowered to the floor was determined using acceleration of a marker on the head of the 5th metatarsal. Recovery *step length* was defined as the anterior-posterior distance between the ankle marker on the recovery foot at foot strike of the first step over the obstacle, and the contralateral ankle marker when the foot was flat on the floor (Pavol et al., 2001). Recovery *step time* was defined as the time elapsed from trip onset to foot strike of the first step over the obstacle. The time of foot strike of the first recovery step was when the vertical ground reaction force exceeded 15 N. *Distance from the ankle to mid-hip at foot strike* was determined using the ankle marker on the foot that first stepped over the obstacle and the mid-point between the hip joint centers. This anterior-posterior distance was used as a proxy measure of the anterior-posterior distance between the recovery foot to center of mass/pelvis at foot strike of first recovery step over the obstacle (Crenshaw et al., 2012; Owings et al., 2001), and positive values indicated the recovery foot ankle was anterior to the mid-hip. Sagittal plane *trunk angle* and *angular velocity* were determined at foot strike of the first step over the obstacle. Finally, *hip height* at foot strike of the first step over the obstacle was determined using the hip marker on the stepping limb. Hip joint center was determined using a functional method (Piazza et al., 2004).

Two types of statistical analyses were performed. First, Barnard's Exact test was used to assess the difference in the fall rate between BMI groups (one-sided test), and the difference in stepping strategy between BMI groups (two-sided test). Effect sizes were estimated using the square of the phi coefficient (φ), which is a special case of the Pearson product-moment correlation coefficient since both variables were binary. Second, the non-parametric Mann-Whitney U-test was used to assess differences in both kinematics at trip onset and response kinematics between BMI groups. These comparisons were made within each stepping strategy to prevent strategy-related differences from confounding potential BMI-related differences. Effect sizes for these analyses were estimated using Cliff's delta (*d*). For random variables X and Y, the *d* statistic is equivalent to the probability that X is larger than Y, minus the probability that Y is larger than X (Cliff, 1993). Larger values of *d* larger correspond to larger effects. Because only four subjects attempted a lowering strategy (see Results), the small sample size precluded an inferential statistical analysis between the three higher-BMI and one lower-BMI subject. Only descriptive comparisons between these subjects were performed. Significant differences where concluded when $p \leq 0.05$, and all statistical analyses were performed using JMP 10 (SAS Institute Inc., Cary, NC).

3. RESULTS

Of the 19 trips that were not characterized as harness-assisted, three were classified as falls and 16 as recoveries (Table 1). Regarding stepping strategy, 70% (7 of 10) of higher-BMI subjects and 89% (8 of 9) of lower-BMI subjects used the elevating strategy, a difference that did not reach significance ($p = 0.213$, $\varphi^2 = 0.05$). None of the elevating responses resulted in falls, the one lower-BMI subject who employed a lowering strategy recovered, and all three higher-BMI subjects who employed a lowering strategy fell. Fall rate was 30% among higher-BMI subjects and 0% among lower-BMI subjects, but this difference did not reach statistical significance ($p = 0.70$, $\varphi^2 = 0.17$). Among the three fallers, harness force did not exceed 30% body weight until 20, 20, and 60 msec after foot strike of the first recovery step over the obstacle, suggesting harness support has little influence on the measurements of kinematic response at foot strike reported below.

TABLE 1 Median and interquartile range [1st quartile, 3rd quartile] of all dependent variables grouped according to BMI group, recovery strategy, and trip outcome.

	Higher BMI Elevating Recovery	Lower BMI Elevating Recovery	Effect size (Cliff's *d*)	Higher BMI Lowering Recovery	Lower BMI Lowering Recovery	Higher BMI Lowering Fall	Lower BMI Lowering Fall
n	7	8		0	1	3	0
Gait speed	1.59	1.59	0.07		1.61	1.68	
(meters/second)	[1.49,1.65]	[1.54,1.63]				[1.59,1.74]	
Phase of gait at onset	54.6	57.9	-0.42		68.6	63.6	
(% stride)	[52.7,58.5]	[56.1,67.3]				[61.6,65.2]	
Trunk angle at onset	3.5	5.0	-0.48		5.2	3.4	
(degrees)	[1.8,4.8]	[3.5,6.7]				[3.3,7.3]	
Trunk ang. vel. at onset	2.2	0.5	0.07		-0.03	7.8	
(degrees/second)	[-0.6,8.2]	[-8.0,9.4]				[5.7,8.5]	
Time to lower foot to floor					0.18	0.27	
(seconds)						[0.14,0.28]	
Recovery step length	60.2	54.9	0.5		53.3	51.7	
(% stature)	[54.7,62.1]	[49.2,59.2]				[41.4,55.5]	
Recovery step time	0.43	0.35	0.75 *		0.48	0.50	
(seconds)	[0.41,0.47]	[0.35,0.41]				[0.49,0.51]	
Ankle to mid-hip at foot strike	11.1	10.2	0.33		10.4	-3	
(% stature)	[8.1,13.9]	[8.4,10.6]				[-4.4,-1.5]	
Trunk angle at foot strike	27.1	32.3	-0.25		33.7	60.4	
(degrees)	[19.1,35.1]	[19.2,36.0]				[53.4,65.6]	
Trunk ang. vel. at foot strike	13.3	25.5	-0.21		-49	95.6	
(degrees/second)	[-41.3,51.5]	[-24.7,70.5]				[54.5,139.2]	
Hip height at foot strike	50.0	52.1	-0.21		52.0	46.4	
(% stature)	[47.7,54.7]	[47.9,56.4]				[41.3,50.1]	

No falls occurred among subjects who employed an elevating strategy. * indicates statistical difference between BMI groups when comparing subjects who employed an elevating strategy and recovered.

Kinematics at trip onset were first explored (Figure 1). For subjects who used an elevating strategy (all were recoveries), no significant differences were found between BMI groups (Table 1) for gait speed (p = 0.862), percent of stride at trip onset (p = 0.183), trunk angle at trip onset (p = 0.155), or trunk angular velocity at trip onset (p = 0.862). For subjects who used a lowering strategy, gait speed and trunk angle at trip onset of the one lower-BMI subject who recovered was within the range of the higher-BMI fallers. Trunk angular velocity at trip onset averaged 7.4 degrees/second higher for the three higher-BMI fallers compared to the one lower-BMI subject who recovered. The percent of stride at trip onset averaged 5.1 % of stride earlier for the three higher-BMI fallers compared to the one lower-BMI subject who recovered.

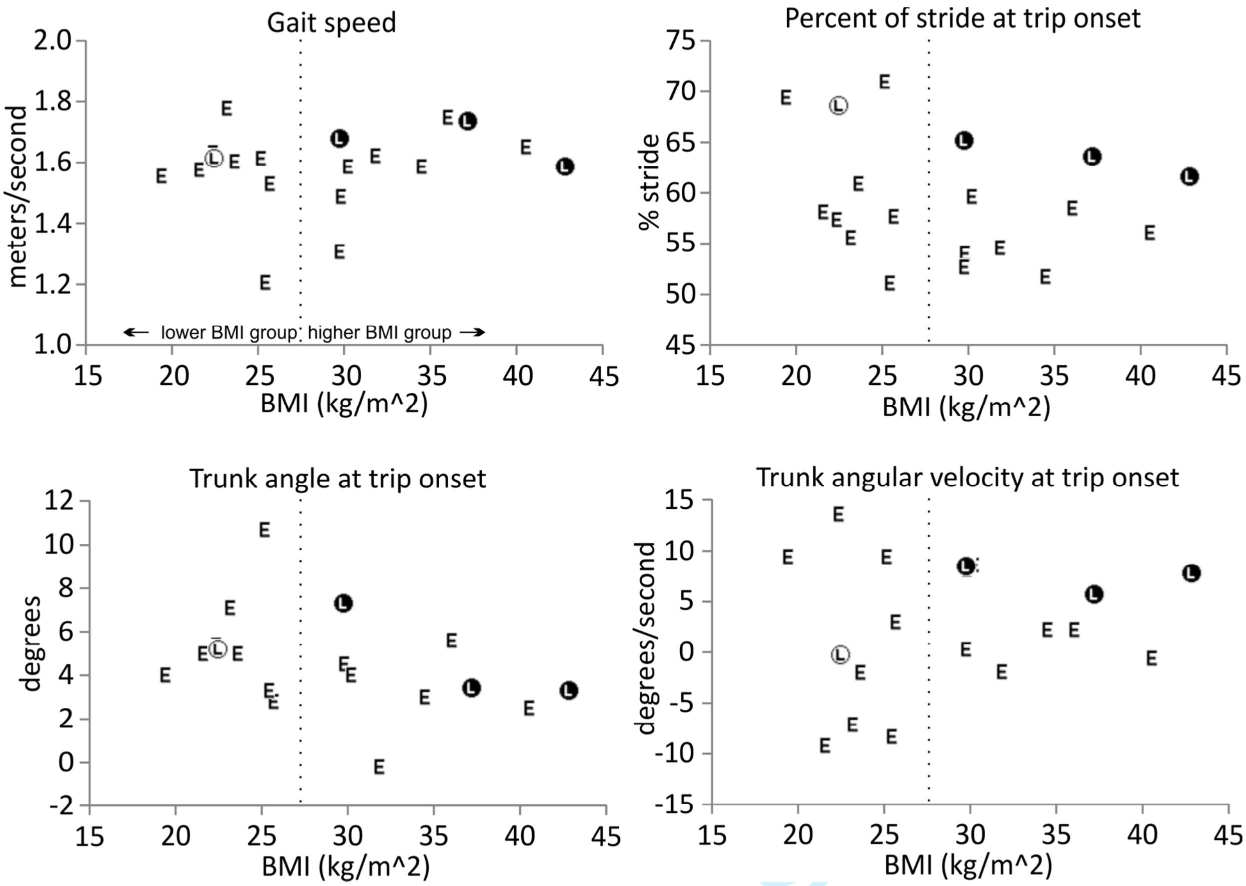

Figure 1. Kinematics at trip onset with respect to subject BMI. "E" = subject who used an elevating strategy and who recovered. White circle with black "L" = subject who used a lowering strategy and recovered. Black circle with white "L" = subject who used a lowering strategy and fell.

The kinematic response to the trip differed to some extent between BMI groups (Table 1; Figure 2). For subjects who used an elevating strategy, median recovery step time was 0.08 s shorter among the lower-BMI group ($p = 0.017$); however, no significant differences were found between BMI groups for recovery step length ($p = 0.118$), distance from ankle to mid-hip at foot strike ($p = 0.353$), trunk angle at foot strike ($p = 0.477$), trunk angular velocity at foot strike ($p = 0.561$), or hip height at foot strike ($p = 0.561$). For subjects who used a lowering strategy, the time to lower the foot to the floor after trip onset was ~50%

(90 ms) longer among two of three higher-BMI fallers compared to the one lower-BMI subject who recovered (Table 1). Some additional qualitative observations between BMI groups were made (Figure 2). Recovery step length of the one lower-BMI subject who recovered was within the range of the three higher-BMI fallers. Recovery step time was higher among all three higher-BMI fallers compared to the one lower-BMI subject who recovered. Distance from ankle to mid-hip at foot strike was not only lower among two of the higher-BMI fallers (data from one higher-BMI faller was missing due to motion capture issues) compared to the one lower-BMI subject who recovered, but was also negative instead of positive, indicating foot strike occurred posterior to the mid-hip position. Trunk angle and angular velocity at foot strike were both higher among all three higher-BMI fallers compared to the one lower-BMI subject who recovered. In fact, trunk angular velocity at foot strike of the one lower-BMI subject who recovered was negative at foot strike, indicating the trunk was rotating backward, whereas it was positive for the three higher-BMI fallers. Hip height at foot strike was lower among all three higher-BMI fallers compared to the one lower-BMI subject who recovered.

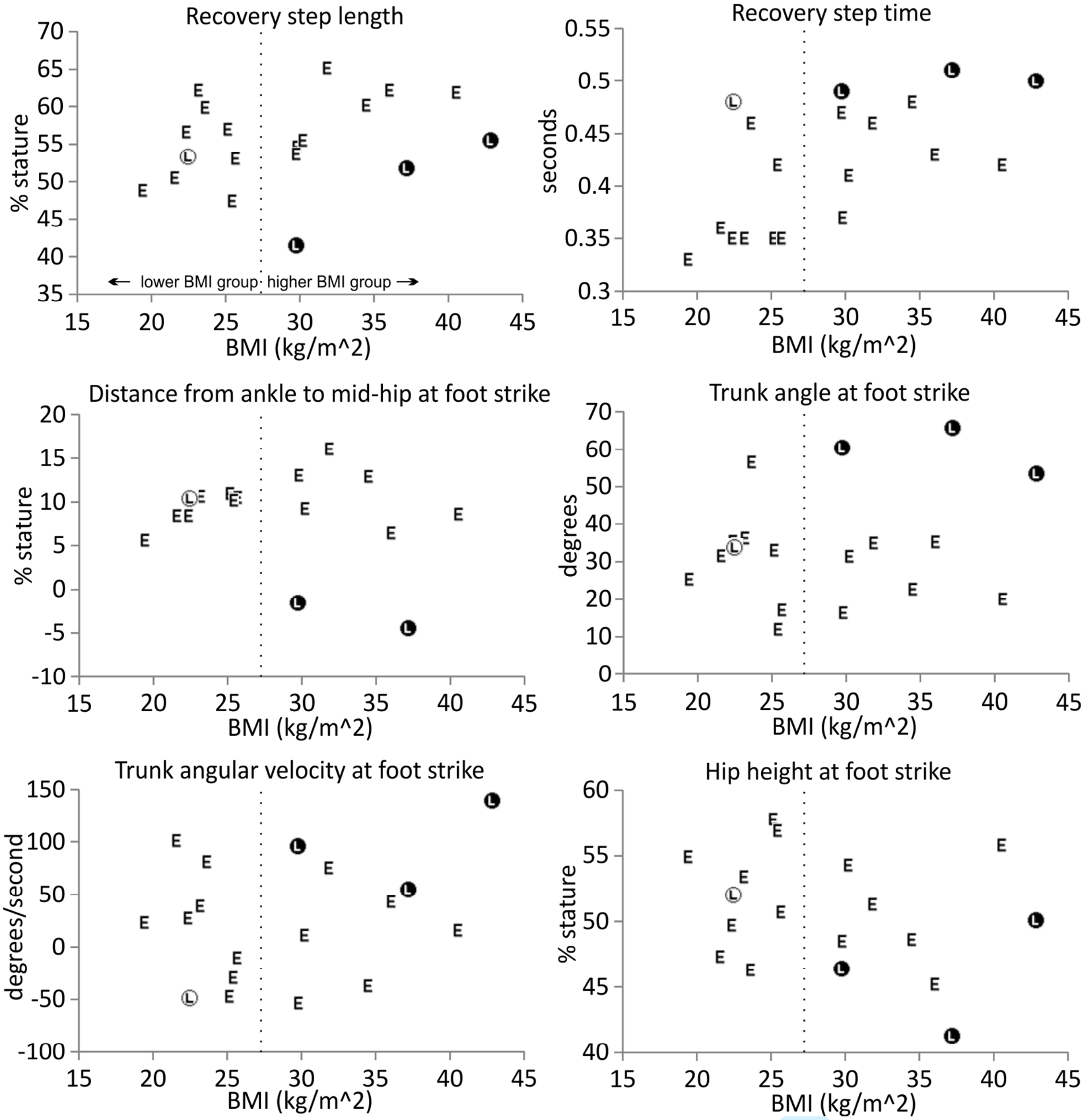

Figure 2. Kinematic response with respect to subject BMI. “E” = subject who used an elevating strategy and recovered. White circle with black “L” = subject who used a lowering strategy and who recovered. Black circle with white “L” = subject who used a lowering strategy and fell. Three data points are missing in the plot of distance from ankle to mid-hip at foot strike due to problems with motion capture.

4. DISCUSSION

The higher rate of falling (Fjeldstad et al., 2008) and fall-related injuries (Janssen et al., 2011) among individuals who are obese may be due, to some extent, to a higher number of trip-induced falls. Therefore, the purpose of this study was to explore obesity-related differences in 1) fall rate resulting from a laboratory-induced trip, 2) kinematics at trip onset, and 3) kinematics during the balance recovery response. We hypothesized that subjects with a higher BMI would exhibit a higher fall rate compared to subjects with a lower BMI. Because the differences in fall rate between higher-BMI (30%) and lower-BMI (0%) subjects did not reach statistical significance, the results from the current study are insufficient to support our hypothesis. Rosenblatt and Grabiner (2012) reported fall rates of 46% among obese (mean and standard deviation BMI = 35.5 ± 3.8) and 25% among non-obese (BMI = 22.7±1.4) older females, but the difference in fall rate also did not reach statistical significance. The lower fall rate found here in both groups may be due to differences in subject-related factors between studies (e.g. our focus on young adults of age 20-30 years while Rosenblatt and Grabiner's subjects were of age ~55-65 years) or experimental factors (e.g. leading to differences in, for example, kinematics at trip onset). Despite both studies reporting a comparable 21-30% higher fall rate among higher-BMI/obese subjects compared to age-equivalent lower-BMI/non-obese subjects, the lack of statistical significance may be due to both studies having modest sample sizes (21 in current study and 25 in Rosenblatt and Grabiner). Performing Barnard's Exact test when pooling the data from the current study and Rosenblatt and Grabiner (2012) would have resulted in a statistically higher fall rate among higher-BMI/obese subjects ($p = 0.039$). These pooled results provide stronger evidence for obesity adversely affecting fall rate after a laboratory-induced trip, which would suggest a greater difficulty executing an effective response to avert a fall after tripping.

We hypothesized kinematics at trip onset would differ between BMI groups. While gait speed did not differ statistically between BMI groups among subjects who used an elevating strategy, the three higher-BMI fallers were all above the 65th percentile in terms of gait speed (% stature/second), with two of these fallers being among the four fastest walkers. Reducing gait speed has been suggested as a strategy to decrease trip-induced fall rates among older adults (Pavol et al., 1999a), and may also be relevant to young adults with higher BMI. However, lowering gait speed may not be desirable in some situations, and may have an unintended consequence of increasing the likelihood of tripping (Garman et al., 2015). Another potentially influential factor was the phase of gait at trip onset, as all three fallers used a lowering strategy response and the use of a lowering strategy is typically associated with a trip onset later during swing. Trip onset for the three higher-BMI fallers was at 62-65% of stride, which was earlier than the trip onset of the one lower-BMI subject who used a lowering strategy to recover (69% of stride). However, this choice of strategy did not seem inappropriate when compared to prior work (Pavol et al., 2001) that reported the successful use of the lowering strategy for recovery at trip onsets ranging from 52-67% of stride. Trunk angle at trip onset did not differ between BMI groups within each stepping strategy. Trunk angular velocity at trip onset, however, was higher among all three higher-BMI fallers compared to the one subject who used a lowering strategy and recovered, but the generally small magnitude of this difference (~10 degrees/second) suggested little clinical importance. In short, lowering gait speed may help to reduce the number of trip-related falls among individuals with higher BMI.

We also hypothesized that subjects with a higher BMI would exhibit a less favorable kinematic response compared to subjects with a lower BMI. Among subjects who used an elevating strategy, recovery step time was the only measure that differed between BMI groups, and was longer among the higher-BMI group. Among subjects who used a lowering strategy, all three higher-BMI fallers exhibited a longer recovery step time compared to the one lower-BMI subject who recovered. As such, higher-BMI subjects exhibited a longer step time, regardless of stepping strategy. These results, combined with the lack of consistent differences in recovery step length between BMI groups, suggest a slower velocity of the stepping foot among higher-BMI subjects, which would be consistent with having to move a more massive lower limb. It should also be noted that interpreting recovery step time can be ambiguous due to both potential detriments and benefits to a longer recovery step time. A longer recovery step time can be a detriment by allowing additional time for the trunk/body to rotate farther forward and faster (due to gravity) relative to the stance foot (Pavol et al., 2001). Conversely, a longer recovery step time can be a benefit if resulting from a greater extension contribution of the support limb to provide additional time and hip height for the recovery step (Pijnappels et al., 2005b). Although our small sample size limited our ability to identify BMI group differences among subjects who employed an elevating strategy, the lack of differences in trunk angle, trunk angular velocity, and hip height at foot strike (which more consistently differ between subjects who fall and recover following a trip) leave open the possibility that the longer recovery step time among the higher-BMI groups was due, at least in part, to a beneficial extension response in the stance limb. Potential obesity-related differences in stance limb kinetics need further investigation.

Among subjects who used a lowering strategy, differences in response kinematics between BMI groups were consistent with a less favorable response among the higher-BMI group (Figure 2). It should be acknowledged, however, that it is not possible to determine the extent to which these differences were due to BMI *per se* because there were no lower-BMI fallers, or higher-BMI subjects who recovered, against whom to compare the observed responses. Nevertheless, the longer time to lower the tripped foot to the floor prior to the contralateral recovery step over the obstacle, the smaller distance from ankle to mid-hip at foot strike, the higher trunk angle and angular velocity at foot strike, and the lower hip height at foot strike, were all consistent with falls after a laboratory-induced trip reported elsewhere (Owings et al., 2001; Pavol et al., 2001; Pijnappels et al., 2005b), and suggests that the basic mechanisms of trip-related falls may be independent of BMI. Trunk angle and angular velocity at foot strike among the higher-BMI fallers appear to be higher than those reported elsewhere among adults age 65 and older (Owings et al., 2001; Pavol et al., 2001), suggesting that higher-BMI subjects may have more difficulty in controlling the angular momentum of the trunk. This would be consistent with a more massive trunk. However, no differences in trunk angle or angular velocity at foot strike were found between BMI groups who used an elevating strategy. This could be due to some other common characteristic among the three higher-BMI fallers that differentiates them from the remaining higher-BMI subjects who employed an elevating strategy and did not fall (e.g. all three higher-BMI fallers were female while six of seven higher-BMI subjects who recovered were male), or could indicate that the use of a lowering strategy among individuals with a higher BMI is particularly challenging.

As noted above, gender may also influence obesity-related differences in the kinematic response to a trip. The higher-BMI group (*n*=10) consisted of six males and four females, yet all three fallers in this group were female. Other studies have reported females (albeit older) to have a higher rate of falling after tripping (Berg et al., 1997; Pavol et al., 1999b) and poorer ability to recover balance (Wojcik et al., 1999), and have attributed these differences to reduced lower extremity strength and power among females (Schultz et al., 1997). Gender differences in lower limb strength/power among obese individuals (Lafortuna et al., 2005; Miyatake et al., 2000) may further increase the risk of trip-induced falls among obese women.

There are several limitations to this study that warrant discussion. First, the limited sample size resulted in limited statistical power and lack of subjects in some BMI-stepping strategy-outcome groups, thus limiting a thorough exploration of these factors. Second, as with any study employing a cross-sectional design, other differences between groups besides the characteristics reported here could have contributed to the results. Third, anticipation effects may have existed since subjects were informed that they may be tripped or slipped. However, we attempted to distract subjects by having them watch a television program and perform numerous trials prior to tripping them without warning, although we acknowledge that these distractions may have influenced their gait. Fourth, the marker placement used to measure trunk kinematics was sensitive to both trunk inclination angle and lumbar flexion. However, both are related to the trunk gravitational moment and momentum that must be overcome during trip recovery. Fifth, harness load among the three subjects who fell were 15%, 17%, and 23% body weight at foot strike. Although these values were greater than zero and therefore had the potential to influence our kinematics measures at foot strike, we felt they were not likely to be substantially influenced because the harness load they did not reach our threshold for harness-assist (30% body weight) or fall (50% body weight) until later. Sixth, soft tissue artifact during motion capture can be elevated among subjects obese subjects (Lerner et al., 2014).

In conclusion, this study provides preliminary evidence that obesity may adversely influence trip-induced falls among young adult workers. Additional larger-scale studies are needed to better understand contributing and modifiable factors that can be targeted via workplace intervention.

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TABLE 1 Median and interquartile range [1st quartile, 3rd quartile] of all dependent variables grouped according tc BMI group, recovery strategy, and trip outcome.

	Higher BMI Elevating Recovery	Lower BMI Elevating Recovery	Effect size (Cliff's *d*)	Higher BMI Lowering Recovery	Lower BMI Lowering Recovery	Higher BMI Lowering Fall	Lower BMI Lowering Fall
n	7	8		0	1	3	0
Gait speed (meters/second)	1.59 [1.49,1.65]	1.59 [1.54,1.63]	0.07		1.61	1.68 [1.59,1.74]	
Phase of gait at onset (% stride)	54.6 [52.7,58.5]	57.9 [56.1,67.3]	-0.42		68.6	63.6 [61.6,65.2]	
Trunk angle at onset (degrees)	3.5 [1.8,4.8]	5.0 [3.5,6.7]	-0.48		5.2	3.4 [3.3,7.3]	
Trunk ang. vel. at onset (degrees/second)	2.2 [-0.6,8.2]	0.5 [-8.0,9.4]	0.07		-0.03	7.8 [5.7,8.5]	
Time to lower foot to floor (seconds)					0.18	0.27 [0.14,0.28]	
Recovery step length (% stature)	60.2 [54.7,62.1]	54.9 [49.2,59.2]	0.5		53.3	51.7 [41.4,55.5]	
Recovery step time (seconds)	0.43 [0.41,0.47]	0.35 [0.35,0.41]	0.75 *		0.48	0.50 [0.49,0.51]	
Ankle to mid-hip at foot strike (% stature)	11.1 [8.1,13.9]	10.2 [8.4,10.6]	0.33		10.4	-3 [-4.4,-1.5]	
Trunk angle at foot strike (degrees)	27.1 [19.1,35.1]	32.3 [19.2,36.0]	-0.25		33.7	60.4 [53.4,65.6]	
Trunk ang. vel. at foot strike (degrees/second)	13.3 [-41.3,51.5]	25.5 [-24.7,70.5]	-0.21		-49	95.6 [54.5,139.2]	
Hip height at foot strike (% stature)	50.0 [47.7,54.7]	52.1 [47.9,56.4]	-0.21		52.0	46.4 [41.3,50.1]	

No falls occurred among subjects who employed an elevating strategy. * indicates statistical difference between BMI groups when comparing subjects who employed an elevating strategy and recovered.

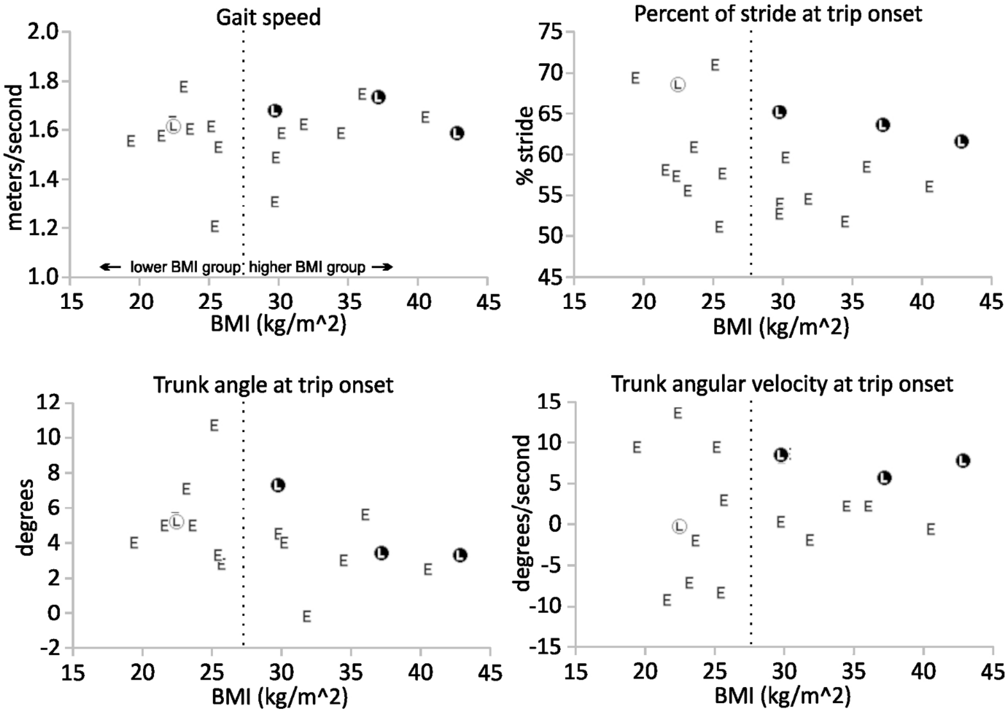

Figure 1. Kinematics at trip onset with respect to subject BMI. "E" = subject who used an elevating strategy and who recovered. White circle with black "L" = subject who used a lowering strategy and recovered. Black circle with white "L" = subject who used a lowering strategy and fell.
163x115mm (300 x 300 DPI)

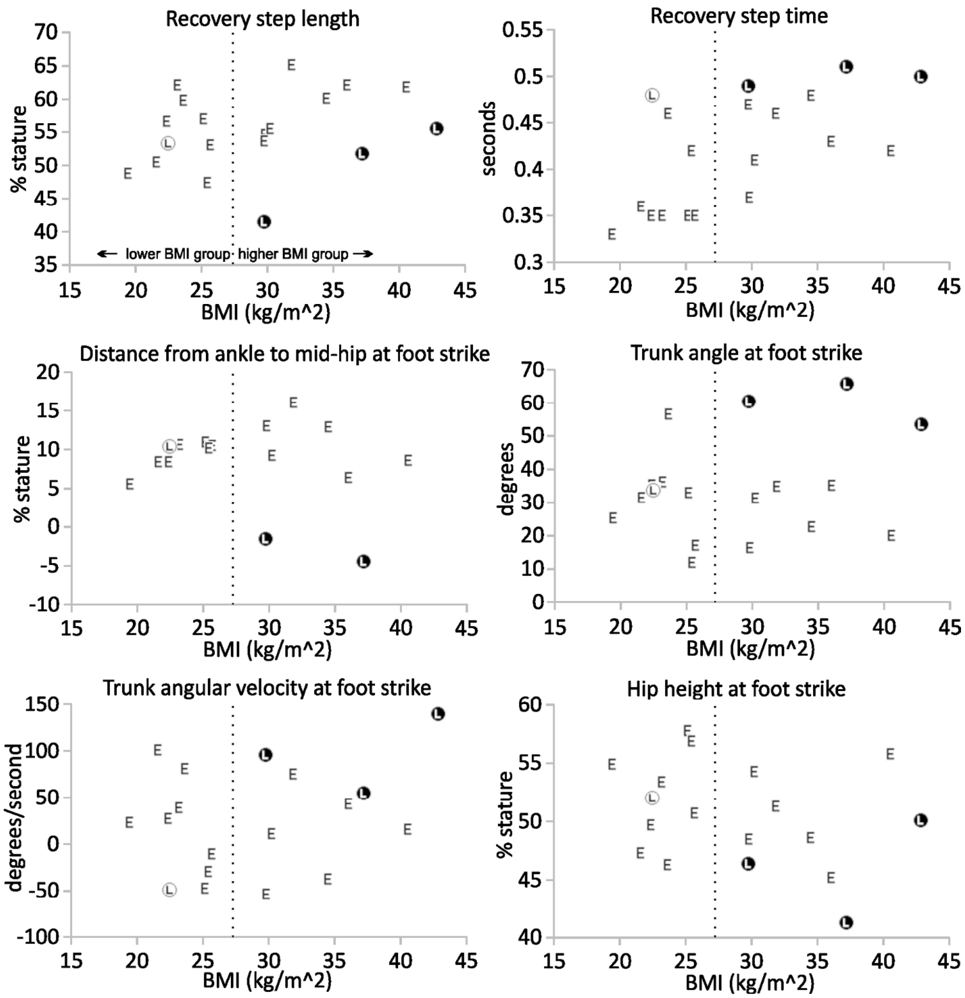

Figure 2. Kinematic response with respect to subject BMI. "E" = subject who used an elevating strategy and recovered. White circle with black "L" = subject who used a lowering strategy and who recovered. Black circle with white "L" = subject who used a lowering strategy and fell. Three data points are missing in the plot of distance from ankle to mid-hip at foot strike due to problems with motion capture.
172x170mm (300 x 300 DPI)