Effects of obesity on slip-induced fall risks among young male adults

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ABSTRACT

Obesity is associated with structural and functional limitations with impairment of normal gait. Although falls have been identified as the most common cause of injuries in the obese, the mechanisms associated with increased fall risk among the obese population are still unknown. The purpose of this study was to investigate the influence of gait adaptations of the obese individuals and its implication on risk of slip initiations as measured by friction demand characteristics. To exclude the aging and gender effects, a total of ten healthy young male adults participated in the study. Kinematic and kinetic data were collected using a three-dimensional motion analysis system and force plates while subjects were walking at their self-selected walking pace. Results indicated that young obese adults walked similarly as their lean counterparts except for exhibiting greater step width and higher transversal friction demand, suggesting that slip-induced fall risks are similar along the horizontal direction, but increased along the transversal direction under certain floor conditions.

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1. Introduction

The global burden of obesity is rising at an alarming rate (Anandacoomarasamy et al., 2008). The World Health Organization estimates that in 2006, more than one billion people are overweight and of these, 300 million are obese. In US, more than one-third of adults, or over 72 million people are obese (Ogden et al., 2007). The prevalence of obesity is not only high, but it continues to rise (e.g., 1991 to 2001, the obesity rates grew by 74%, (Mokdad et al., 2003)). The latest figures from the Centers for Disease Control and Prevention (CDC) also indicated that obesity is a significant public health problem in the United States. Obesity is often associated with structural and functional limitations that may limit movement control (Hills et al., 2002) and influence gait patterns (i.e., slower walking velocity, longer double support time, and greater step width) (Hills and Parker, 1991; Lai et al., 2008; McGraw et al., 2000; Sharma, 2001; Spyropoulos et al., 1991). One of the many concerns is its association with an increased risk of falls and subsequent injuries. Falls have been identified as the most common (36%) cause of injuries in the obese (Matter et al., 2007), and obese adults fell almost twice as frequently (27%) as their lean counterparts (15%) per year (Fjeldstad et al., 2008). Although epidemiological studies clearly indicate the increased risk of falls in the obese population, the mechanisms associated with this increased fall risk is still unknown. Furthermore, it is unclear how gait adaptations in the obese population may increase the risk of falls.

In the context of slip induced fall accidents, slip/fall risks have been linked to several initial gait measures. It is believed that slip is initiated when the frictional force ($F\mu$) opposing the movement of the foot is less than the horizontal shear force (Fh) at the foot during the heel contact phase of the gait cycle (Hanson et al., 1999; Lockhart et al., 2003), although that falls are not necessary the consequences of slips. Required coefficient of friction (RCOF) as measured by horizontal shear force divided by vertical ground reaction force is thought to represent the general friction demand (minimum coefficient of friction that must be available or "required") at the shoe-floor interface to prevent initiation of forward slipping (Redfern and Andres, 1984). Previous studies suggested that RCOF is associated with several gait parameters (Cooper et al., 2008; Gronqvist et al., 2001; Kim et al., 2005; Lockhart et al., 2003; Redfern et al., 2001). For example, walking velocity directly affects the magnitude of shear force (Fh), and therefore also has a direct effect on RCOF (Kim et al., 2005). An increase in walking velocity usually increases the RCOF and risk of slip initiation (Gronqvist et al., 2001; Redfern et al., 2001). Initial gait characteristic such as slower transitional acceleration of the whole-body center of mass (COM) may affect RCOF due to the increase in horizontal foot force (Kim et al., 2005; Lockhart et al., 2003). Transitional acceleration (TA) is the relative horizontal COM differences between velocity of the whole body COM before (VCOMb) and after (VCOMa) heel contact (Lockhart et al., 2003). Studies also suggested that changes in step length may influence RCOF (Cooper et al., 2008). As such, altered gait pattern of the obese population may further influence the initial gait parameters and increase the potential risks for slip-induced fall accidents.

The objective of the current study is to investigate the effects of obesity on gait and related slip risks as measured by RCOF.

Since both the obesity and gait may be further influenced by the gender and aging effects, the focus of this study is on the younger healthy male subjects. It was hypothesized that obesity (excess body fat as measured by Bioelectrical Impedance Analysis) will influence the kinematic and kinetic gait variables related to slip propensity (i.e. RCOF) leading to higher likelihood of a slip being initiated and may increase the risk of slip-induced falls.

2. Methods

2.1. Subjects

To exclude the aging and gender effects, a total of ten young healthy male adults, including five lean (mean age 24.6 ± 2.3 years, height 179.8 ± 4 cm, mass 75.9 ± 13.6 kg, BMI 23.4 ± 4.0 kg/m^2, body fat percentage $14.8\% \pm 1.8\%$) and five obese (mean age 24.6 ± 4.3 years, height 179.3 ± 5.8 cm, mass 108.3 ± 9.4 kg, BMI 33.7 ± 2.8 kg/m^2, body fat percentage $33.6\% \pm 2.4\%$) from Virginia Polytechnic Institute and State University population who did not have any musculoskeletal injuries that affected their ability to perform the walking activity in the experiment participated in the study. Informed consent was approved by the Institutional Review Board (IRB) of the Virginia Polytechnic Institute and State University and obtained prior to the experiment. Participants' weight was measured to the nearest 0.1 kg on a Salter 200 scale, with the subjects wearing no shoes and only light clothing. Height was measured to the nearest 0.1 cm with a wall-mounted stadiometer. Obesity was defined as the body fat greater than 25% of the total body mass (Romero-Corral et al., 2008) as well as BMI of above 30 kg/m^2 (Lai et al., 2008).

2.2. Equipment

Walking trials were conducted on a linear walkway ($1.5 \text{ m} \times 15.5 \text{ m}$) embedded with two force plates (BETEC #K80102, Type 45550-08, Bertec Corporation, OH 43212, USA). Kinetic data from the force plates were collected at a sampling rate of 1200 Hz. Experimental shoes were provided to participants to minimize shoe sole differences. Twenty-three reflective markers were placed bilaterally over the second metatarsal head, lateral malleolus, calcaneus, lateral femoral condyle, anterior superior iliac spine, clavicle, acromioclavicular joint, lateral humeral condyle, ulnar stylus, third metacarpal head and ear (Lockhart et al., 2003; Parijat and Lockhart, 2008). A six-camera ProReflex system (Qualysis Medical AB, Gothenburg, Sweden) was used to collect three dimensional position data of the participants while walking. Kinematic data from the camera were sampled and recorded at 120 Hz. A Bioelectrical Body Composition Analyzer (RJL systems, Inc., MI 48035, USA) was used to measure the body fat percentage.

2.3. Body fat percentage measurement and experiment protocol

All participants were required to report to the lab in the morning after avoiding the breakfast and drinking water (Hulens et al., 2003). Body mass composition was obtained using the four-point method (Baumgartner et al., 1998; Hulens et al., 2003). Two current driving ECG disposable electrodes were attached to the dorsal side of the right hand near the fingers and the dorsal side of the right foot near the toes. Another two voltage sensing ECG disposable electrodes were attached to the dorsal side of the right wrist and ankle, proximal to the current driving electrodes. The participants were asked to lay supine with legs shoulder width apart and right arm at a slight angle to the rest of the body. Resistance and reactance readings were obtained after the electrodes were attached. EHANES-III equations were used to calculate fat percentage (Chumlea et al., 2002).

After the test, brief refreshment was provided to each participant. The participants were then asked to change to lab clothes and shoes and instructed to walk at a self-selected pace across the linear walkway for 10–15 min. The force plate and kinematic data were collected once the participants felt comfortable and produced consistent repetitive gait, i.e. the participants' feet landed on the center of the force plate and in the desired sequence (left foot on the first force-plate and then right foot on the second force-plate). Six gait trials were recorded for each participant to represent the mean.

2.4. Computation of gait parameters

The horizontal required coefficient of friction (HRCOF) is defined as the ratio of horizontal ground reaction force to vertical ground reaction force (Redfern and Andres, 1984) and similarly, the transversal required coefficient of friction (TRCOF) is defined as the ratio of transversal ground reaction force to vertical ground reaction force. Resultant required coefficient of friction (RRCOF) is defined as the ratio of resultant ground reaction force (square root of the sum of square of
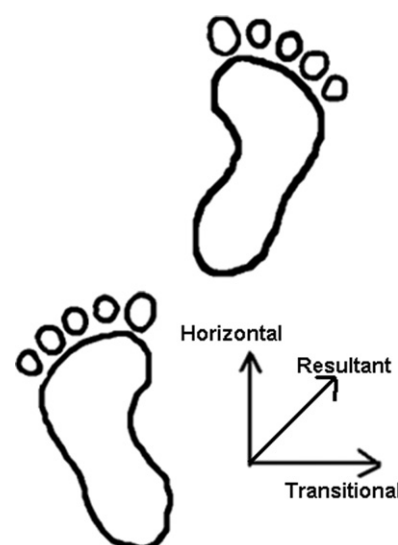

Fig. 1. Directions of different components of ground reaction force.

horizontal ground reaction force and square of transversal ground reaction force) to the vertical ground reaction force (Fig. 1). These values represent the minimum required coefficient of friction between the shoe and floor interface to prevent slipping (Perkins, 1978). Heel contact velocity is a one-dimensional velocity along the horizontal direction. The instantaneous horizontal heel velocity (νhc) at heel contact was calculated utilizing heel velocities in the horizontal direction at the foot displacement of 1/120 s (Δt) before and after the heel contact phase of the gait cycle using the formula:

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

(Cham and Redfern, 2001; Lockhart et al., 2003). Walking velocity (WV) was obtained from the whole-body center-of-mass (COM) velocity during forward progression (Lockhart et al., 2003). Transitional acceleration (TA) is the relative horizontal COM differences between velocity of the whole body COM before (VCOMb) and after (VCOMa) heel contact (Lockhart et al., 2003).

$$\dot{v}_{COM} = (v_{COMb} - v_{COMa})/\Delta t$$

Step length (SL) was calculated from the distance between consecutive positions along the progression direction of the heel contacting the floor (Lockhart et al., 2003). Step width (SW) is determined as the medial–lateral distance between the locations of sequential left and right heel contact (Owings and Grabiner, 2004). Center-of-mass vertical excursion (COMz) and the center-of-mass medial–lateral excursion (COMy) (Inman et al., 1994; Saunders et al., 1953) were calculated as the extreme displacement of COM in both directions using the body segmental technique (Orendurff et al., 2004). All of the computations were performed by custom-made programs in MATLAB 2010b (The Math Works Inc., Natick, MA, USA).

2.5. Statistical analysis

There was one independent variable in this experiment, which has two levels—non-obese, and obese and ten dependent variables (HRCOF, TRCOF, RRCOF, HCV, WV, TA, SL, SW, COMz, COMy). For each variable, mean and standard deviation were calculated. One-way between-subject ANOVA was performed on each of the dependent variables with groups (non-obese and obese) as the independent variable (Kunter et al., 2004). JMP (SAS Institute Inc., Cary, NC, USA) was used to carry out the statistical analysis. The level of significance was set at $\alpha < 0.05$. Bivariate analysis was performed to examine the correlation between the different dependent measures.

3. Results

The mean and standard deviation with the statistical results are provided in Table 1. The one-way ANOVA indicated that the participants from the two groups walked with similar HRCOF and RRCOF, but obese group walked with higher TRCOF ($F(1,8) = 12.0452$, $p = 0.0084$). Fig. 2 illustrates one participant's horizontal coefficient-of-friction pattern along with vertical and horizontal ground reaction forces from heel-contact to toe-off . Heel-contact

Table 1
Summary of kinematic and kinetic parameters during normal walking trials for both non-obese and obese groups.

Variables	Groups		ANOVA
	Non-obese	**Obese**	
HRCOF	0.17 (0.02)	0.18 (0.02)	N.S.
TRCOF	0.05 (0.01)	0.07 (0.01)	[a]
RRCOF	0.18 (0.02)	0.19 (0.02)	N.S.
HCV	1219.54 (248.45)	1654.99 (248.15)	N.S.
WV	1186.08 (83.14)	1210.21 (86.22)	N.S.
TA	1232.99 (63.31)	1405.43 (190.14)	N.S.
SL	800.08 (80.95)	805.18 (41.40)	N.S.
SW	115.01 (17.71)	160.09 (16.88)	[a]
COMz	53.68 (8.29)	62.39 (7.25)	N.S.
COMy	47.54 (5.27)	52.89 (19.32)	N.S.

N.S. not significant, $^{*}p < 0.05$. HRCOF, horizontal required coefficient of friction; TRCOF, transversal coefficient of friction; RRCOF, resultant required coefficient of friction; HCV (mm/s), heel contact velocity; WV(mm/s), walking velocity; TA (mm/s^2), whole body COM transitional acceleration; SL (mm), step length; SW (mm), step width.

[a] $p < 0.01$. Results are in the form of mean (SD).

and Toe-off are defined as vertical ground reaction force exceeding 10 N, and less than 10 N, respectively, (Lockhart et al., 2003). Fig. 3 illustrates the same participant's transversal coefficient-of-friction and vertical and transversal ground reaction forces from heel-contact to toe-off. Time and value of HRCOF and TRCOF are marked as dash line in both figures.

Participants from both groups walked with similar walking velocity, heel contact velocity and transitional acceleration. Participants from obese group walked with wider step width ($F(1,8) = 14.5985$, $p = 0.0051$). The step length was similar in both groups. Obese and non-obese groups showed a similar medial–lateral whole-body center-of-mass excursion but greater vertical whole-body center-of-mass excursion ($F(1,8) = 4.1676$, $p = 0.076$), (Table 1).

The bivariate correlation between the different dependent variables indicated that transversal coefficient of friction was positively correlated with step width ($r = 0.6663$, $p = 0.04$).

4. Discussion and conclusion

The objective of this study is to evaluate the effects of obesity on gait and related slip risks as measured by friction demand characteristics. Epidemiological findings indicated that obese individuals have more prevalence of falls, however, the mechanism of obesity associated falls is not clear. We hypothesized that excess body fat mass as measured by Bioelectrical Impedance Analysis (BIA) will influence the kinematic and kinetic variables related to slip propensity (i.e. RCOF in both horizontal and transversal directions) leading to higher risk of slip-induced falls. To exclude the gender and aging effects, we focused on the young healthy male groups.

The results did not show any significant differences in horizontal required coefficient of friction (HRCOF) or resultant required coefficient of friction (RRCOF) between the non-obese and obese groups. The HRCOF and RRCOF values obtained from this study are within the range of the literature reported value: between 0.17–0.24 (Lockhart et al., 2003; Parijat and Lockhart, 2008). The RCOF has been implicated as an important predictor variable related to slip propensity and outcome of falls (Lockhart et al., 2003; Redfern and Bidanda, 1994). As HRCOF is the ratio of horizontal and vertical ground reaction forces, although both forces were found higher among obese population (Browning and Kram, 2006; DeVita and Hortobagyi, 2003; Mesier et al.,

1996), the ratio did not differ, which suggested that the slip-induced fall risks along the horizontal direction are not different between young obese male and their normal weight counterparts. Furthermore, the results also indicated that obese participants walked with similar gait (walking velocity, heel contact velocity, transitional acceleration and step length) as shown in Table 1. Although ground reaction forces were found to be higher among obese population, as no gait adaptations were observed along the horizontal walking direction, it appears that the link between obesity, gait adaptations and increased risks of slip-induced falls in this direction was not supported. However, in terms of transversal components of slip-induced fall risks, we found that transversal required coefficient-of-friction (TRCOF) was significantly different between obese and non-obese groups. TRCOF represents the general frictional coefficient at the shoe-floor interface for potential lateral slipping. As seen in Fig. 2, TRCOF occurs near the first peak of the medial–lateral ground reaction force during the weight acceptance phase (0–250 ms) of the gait cycle (Winter, 1980). An increase in TRCOF during the critical period of weight acceptance may lead to a greater possibility of a slip initiation transversally if (1) the floor frictional property differs in horizontal and transversal directions and (2) the friction between the heel and the floor in the transversal direction is reduced due to contamination of the floor surface. Since the value of the TRCOF is between 0.05 and 0.07, potential for slip risks are highly dependent on the shoe-floor interface conditions. When the friction demand (in this case, obese individuals demand of 0.07 versus normal weight individuals demand of 0.05) is greater than the friction available, for example, when walking on vinyl tile floor surface with European standard G2AE shoe–sole material under wet condition, the friction coefficient is 0.05 (Chang and Matz, 2001), or walking on glycerol contaminated stainless steel floor with thermoplastic rubber sole material, the friction coefficient is 0.05 (Gronqvist, 1995), the likelihood of slip initiation is increased significantly among the obese individuals. Although implicated, recent research also found that certain individuals (not only the obese) walked with a greater transversal force (Chang et al., 2011) and, exhibited a greater lateral slip tendency (Troy et al., 2008). As no research to date have evaluated the transversal components of friction demand characteristics that may be related to the slip-induced fall risks among this population, future studies examining the fall risks in relation to the transversal required coefficient of friction are warranted. As such, in order to better identify obese-related slip-induced fall risk characteristics, future study incorporating slip perturbations are warranted.

TRCOF was positively correlated to step width (SW). SW is determined as the medial–lateral distance between the locations of sequential left and right heel-contacts (Owings and Grabiner, 2004). We found that obese individuals walked with a significantly greater step width than their normal-weight counterparts. This finding is in agreement with previous studies investigating gait of the obese population (Lai et al., 2008; Spyropoulos et al., 1991). A possible explanation for the wider gait patterns associated with obesity could be due to the excessive adipose tissue between the thighs (Ellabban and Hart, 2004). The increased mass on the thighs in obese group may cause increased inertia (Lebiedowska and Polisiakiewiez, 1997) to move forward, and required more effort to maintain the same level of stability (Donelan et al., 2004) in the medial–lateral direction as their lean counterparts, and further increase the transversal ground reaction forces increasing the TRCOF.

This study was carried out to investigate the effects of obesity characterized by body fat percentage on gait characteristics, and related slip-induced fall risks. Researchers have reported that there is significant difference in walking velocity and step
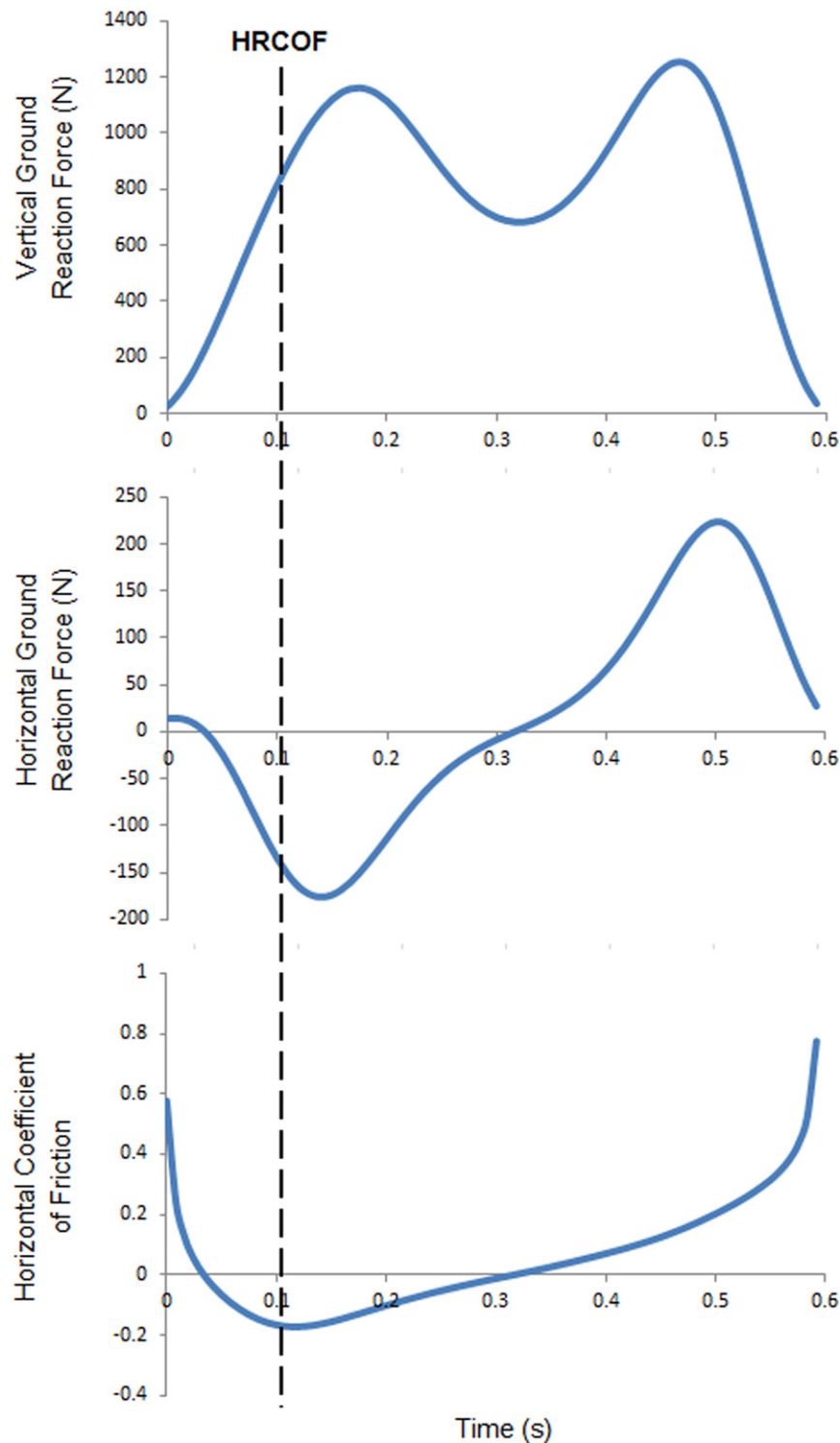
Fig. 2. Horizontal coefficient of friction and its corresponding ground reaction force profiles.

length between obese and non-obese populations (DeVita and Hortobagyi, 2003; McGraw et al., 2000), which we did not find in this study. The reason may be that different age groups were used. One study included both young and middle aged obese and non-obese subjects, the other investigated obese versus non-obese boys, and whereas our study only focused on young adults whose age are between 20 and 30 years old. As such, in order to investigate the true nature of falls risk among obese population, future study should be carried out investigating different age groups (i.e., middle-aged and older adults).

Our results also showed that obese individuals have greater COM vertical excursions (COMz) compared to their lean counterparts, and the values obtained from this study are in agreement with the literature (Orendurff et al., 2004). Hisang and Chang (2002) suggested that the added load carried in front of the whole-body COM increased momentum pulling the COM forward into the next step. Similarly, accumulated body fat on the abdominal and thighs (Cereda et al., in press; Ellabban and Hart, 2004) may increase momentum pulling the COM of the whole-body forward and vertically. Extremes in the vertical displacement of the COM
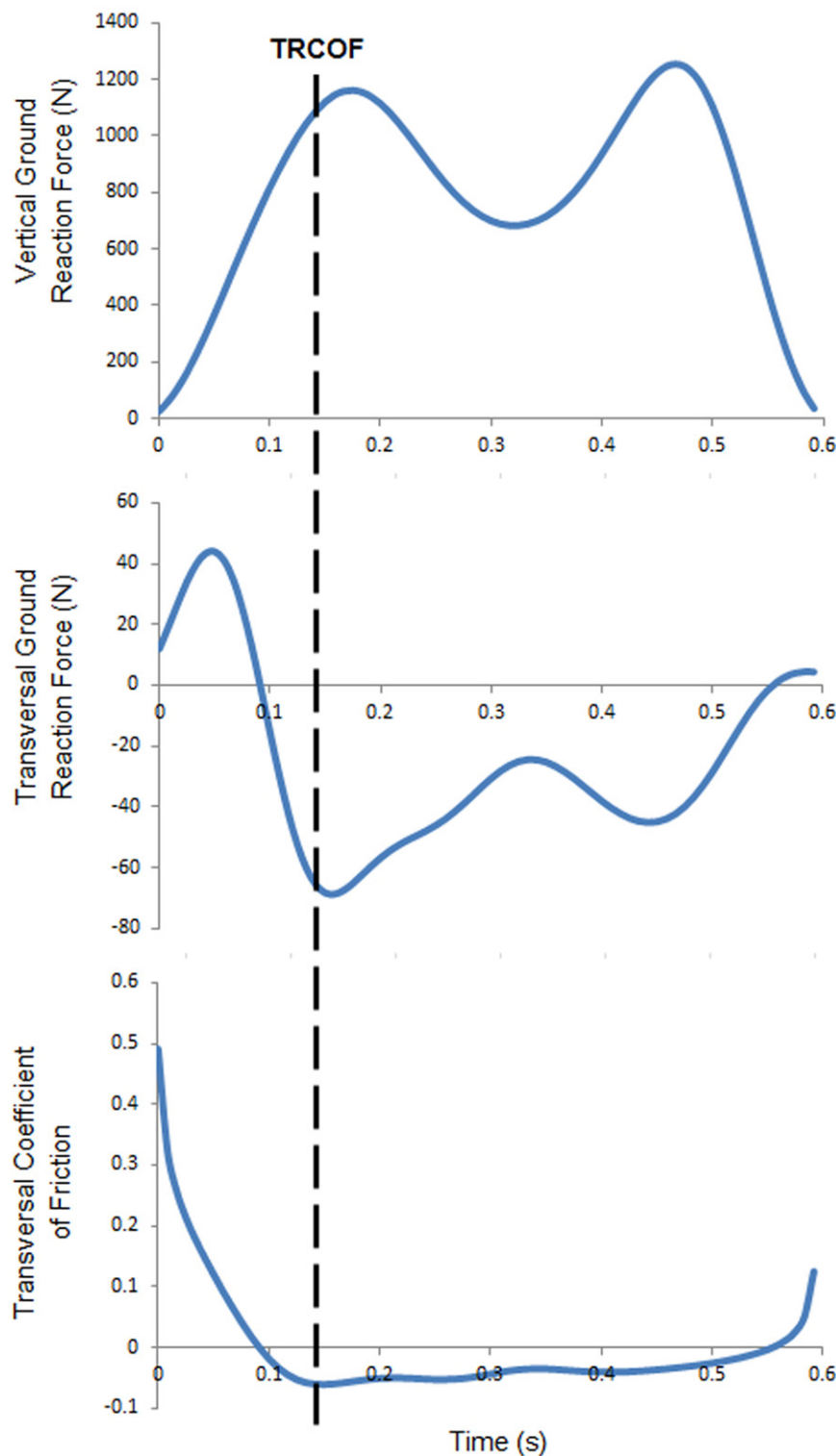
Fig. 3. Transversal coefficient of friction and its corresponding ground reaction force profile.

are thought to be energetically and metabolically costly. Researchers reported that COMz is highly correlated with oxygen consumption during human gait (Kerrigan et al., 1995). As a result, obese individuals may spend significantly more mechanical and metabolic energy than their lean counterparts due to their larger COM vertical excursions. Locating some of the anatomical landmarks (i.e., iliac spines and femoral condyles) over which markers are placed can be challenging in some obese subjects. Furthermore,

the influence of soft tissue motion on the location of the markers relative to the landmarks can induce noise in the calculation. Additionally, the equation used for center of mass estimations may or may not be accurate for obese subjects. The center of mass estimations using different set of equations for both obese and non-obese populations are warranted.

In conclusion, young obese adults walked similarly as their lean counterparts except for exhibiting greater step width and

higher transversal friction demand characteristics, suggesting that slip-induced fall risks are similar along the horizontal direction, but increased risks along transversal direction under certain floor conditions.

Acknowledgment

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