

**MAXIMUM ABSOLUTE AND RELATIVE JOINT TORQUES DURING RECOVERY  
FROM A SIMULATED TRIP**

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Michael James Whitley

(ABSTRACT)

Previous studies have shown that obesity negatively affects balance during quiet standing, yet little is known about its effect on the ability to recover after a postural perturbation. The purpose of this thesis was to investigate the effects of obesity on single-step balance recovery from an incipient forward fall. Eight obese (BMI =  $33.2 \pm 2.4$ ) and eight non-obese (BMI =  $24.8 \pm 1.8$ ) participants were released from a static forward lean and asked to recover their balance with a single step. Lean angle was progressively increased until they could no longer recover balance with a single step. Peak joint torques and relative effort during balance recovery were calculated and compared across the groups. Obese participants achieved a smaller maximum lean angle compared to non-obese participants. During balance recovery, obese participants exhibited higher ankle plantar flexor torques and relative effort. Trends also suggested higher relative hip extensor effort in the obese. Obese adults exhibited a poorer ability to recover from a forward fall with a single step. In addition, obese adults used a higher percentage of their total hip and ankle strength compared to non-obese adults during balance recovery. This suggests that the poorer ability of recovering from a forward fall in the obese may be related to increased exertion levels during balance recovery.

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# CHAPTER 1

## LITERATURE REVIEW

### **I. Significance**

One of the most significant epidemiological trends of the last 20 years is the increased prevalence of overweight and obesity. Since 1980, the prevalence of adult obesity in the United States has doubled, and the prevalence of childhood overweight has tripled (Flegal et al. 2002, Ogden et al. 2002, Hedley et al. 2004). More recently, the prevalence of adult obesity in the US has grown from 27.5% in the years 1999-2000 to 31.1% in 2003-2004 (Ogden et al. 2006). As a result of this trend, the World Health Organization reported one billion individuals world-wide as being overweight or obese (Puska et al. 2003). The high prevalence of obesity is problematic because obesity is associated with numerous medical conditions including an increased risk of falling (Lord et al. 1991, Lord et al. 1993, Baloh et al. 1995).

In order to better understand the contributors affecting falls, two general sources have been identified: environmental and intrinsic contributors. Environmental contributors to falls can include the condition of walking and working surfaces, terrain, weather, and lighting conditions (Lipscomb et al. 2005). In order to better understand the intrinsic contributors to falls, it is first important to understand the biomechanical factors critical to balance recovery. The overall purpose of this literature review and thesis is to better understand and quantify the effects of obesity on these biomechanical factors and how that relates to balance recovery in the obese population.

The literature review is organized as follows. First, current research investigating the effects of obesity on balance recovery is presented in groups of similar studies. Next, a simple inverted pendulum model of the obese adult will be presented to illustrate the results of the

published studies and highlight areas where additional research is needed. Lastly, the background and motivation for the study of this thesis is presented.

## **II. Summary of Balance Recovery Obesity Research**

Extensive research has been done on the nature of obesity and its causes, but there remains a dearth of information regarding the functional limitations imposed by overweight and obesity (Wearing et al. 2006). This part of the literature review summarizes the work to date related to the effects of obesity on postural sway and balance and on muscle strength and power.

### **A. Postural Stability and Balance**

Research on the effects of obesity on postural sway is limited in both quantity and scope. The focuses of these studies has been on identifying the effects of obesity on postural sway during quiet standing, investigating the effect of weight loss on postural sway in the obese, and finally using the experimental results to develop a mathematical model of postural sway in the obese.

Goulding et al. (2003) investigated the effect of obesity on postural sway in 93 boys using the Bruininks-Oseretsky balance test. The Bruininks-Oseretsky balance test consists of three tests of quasi-static balance including standing on preferred leg on the floor and on a balance beam, and five tests of dynamic balance including tests of walking on the floor and on a balance beam (Wilson et al. 1995). Goulding et al. found a significant correlation between BMI and increased postural sway in the obese boys. Using data collected during quiet standing trials in 10 obese and 10 non-obese subjects, McGraw et al. (2000) reported that there was a significant increase in postural sway, as indicated by increased maximum displacement and RMS of the center of pressure (COP), in both the medial-lateral and anterior-posterior directions.

They suggested that the increase in postural sway in the obese may be attributed to an excess noncontributory mass (McGraw et al. 2000).

Hue et al. (2007) built from these studies and investigated the contribution of body weight to the prediction of balance stability. They performed quasi-static balance trials, both with and without vision, on a force platform for 59 males of varying age with mean BMI ( $\pm$ SD)  $35.2 \pm 11.7 \text{ kg/m}^2$ . Using mean COP speed as an indicator of balance stability, they found through stepwise multiple regression that body weight accounted for 52% of the variance of balance stability with vision, and 54% of the variance of balance stability without vision. Hue and colleagues' work supported the conclusion that body weight may be an important risk factor for falling (2007).

Maffiuletti et al. (2005) investigated the effects of obesity on postural sway using a single limb stance on a moveable platform that allowed movement exclusively in the medial-lateral direction. This is important because it addresses potential biomechanistic differences in maintaining dynamic postural stability compared to quiet standing. Nineteen non-obese (BMI =  $23.3 \pm 2.3 \text{ kg/m}^2$ ) and 20 obese (BMI =  $44.3 \pm 6.8 \text{ kg/m}^2$ ) participants attempted to maintain the horizontal orientation of the freely moving platform during 30 second standing trials. Maffiuletti and colleagues found that the time of balance maintenance (i.e. the longest period sustained without use of an assistive handrail) on the moveable platform was shorter and the medial-lateral sway of the trunk was larger in obese than in non-obese group. A follow-up study using the same methods, performed by Greve et al. (2007), found that high BMI demands more trunk displacements to maintain postural balance. The conclusion was made, similar to Maffiuletti et al., that adipose tissue accumulation and body mass increases can cause reductions in balance and be a major contributing factor concerning falls.

The study by Maffiuletti et al. (2005) was also one of the first to address the effects of weight loss on postural stability and balance. A three-week body weight reduction (BWR) program was implemented for 10 of the 20 obese participants that entailed dieting, moderate physical exercise, nutritional education, and psychological counseling. A sub-group of the BWR participants also took part in several sessions of specific balance training on a moveable platform. This training was included to differentiate training effects from weight reduction effects in the obese subjects. It was found that the BWR sub-group exhibited a significant increase in the time of balance maintenance and reduced trunk sway during the standing trials on the moveable platform compared to the sedentary obese participants. Moreover, it was found that BWR plus specific balance training significantly enhanced the time of balance maintenance and reduced trunk sway more than BWR alone. Therefore, they concluded that both weight loss and balance improvement rehabilitation may be able to reduce the propensity of overweight individuals to fall (Maffiuletti et al. 2005).

More recently, Teasdale et al. (2007) performed a longitudinal study to quantify postural stability changes in the obese with weight loss. COP measures were made on a force platform both prior to and after weight loss in men. Three groups were defined: a control non-obese group of 16 men ( $BMI = 22.7 \pm 2.2 \text{ kg/m}^2$ ), an obese group of 14 men that underwent a hypocaloric specific diet ( $BMI = 33 \pm 3 \text{ kg/m}^2$ ), and a morbidly obese group of 14 men that underwent a bariatric surgery ( $BMI = 39.9 \pm 7.3 \text{ kg/m}^2$ ). Using data collected from balance trials on a force platform, COP measures along the antero-posterior and medio-lateral axes for conditions with and without vision were performed using a force platform prior to weight loss and at regular intervals up to 12 months after the intervention. The results showed a strong linear relationship between weight loss and improvement in balance control as measured by mean COP

speed. The conclusion was made that losing weight improves balance control, and that the degree of improvement is directly related to the amount of weight lost. This conclusion is in support of the previous research of Maffiuletti et al. (2005).

Corbeil et al. (2001) were the first to attempt to use the experimental results of previous studies to build a mathematical model of the obesity effects on postural stability. This is important because the development of a research model allows for more rapid and efficient investigations into biomechanical obesity effects than traditional human testing. Using a 15-segment humanoid, Corbeil et al. examined the impact of abnormal distributions of fat, particularly in the abdomen, on the control of postural stability during a perturbation from a quiet, bipedal stance. The results show that obese adults have to generate a significantly higher ankle joint torque to recover balance. This was attributed to the anterior displacement of the center of mass of the obese adults, which brings them closer to their boundaries of stability during quiet standing than non-obese adults (Wearing et al. 2006). Therefore, it was indicated that an elevated accumulation of body fat, particularly in the abdominal area, might also decrease the body balance and increase the propensity for falls in obese adults.

## **B. Muscle Strength and Power**

Extensive research has also been conducted to investigate the obesity effects on muscle strength and its potential to cause functional limitation. One of the earliest studies investigating the interaction between obesity and muscle strength was by Kitagawa et al (1978). They measured hand-grip strength, elbow flexion strength, trunk extension strength, knee extension strength, and body composition for 59 men with body fat percentages between 6.2 - 35.6%. While they found that the obese men presented with greater absolute strength, obese men had lower muscle strength than non-obese men when expressed as a percentage of body weight. This

is important because it is the first time that relative strength, muscle strength expressed as a percentage of body weight, was presented as an indicator of functional limitation in the obese. Using similar methodology, Blimkie et al. (1990) came to similar conclusions that obese subjects have reduced relative isometric and isokinetic knee extensor strength compared to non-obese. Maffiuletti et al. (2007) later focused their analysis of obesity-related muscle strength changes to only the quadriceps muscles. They found that obese subjects displayed a 20% higher absolute but 32% lower relative muscle torque and power than their non-obese counterparts (Maffiuletti et al. 2007). This focus on the quadriceps muscle group is important because knee extensor strength has been shown to play an important role in the lower extremity function, particularly in measures of dynamic balance (Jadelis et al. 2001).

Lafortuna et al. (2005) applied similar muscle strength analysis techniques to the morbidly obese. Ninety-five morbidly obese subjects ( $BMI = 41.2 \pm 4.4 \text{ kg/m}^2$ ) and eighteen non-obese, control subjects took part in this study that investigated muscle strength and power output as a function of body composition via a jump test designed by Bosco et al (1983). Lafortuna and colleagues found that the morbidly obese exhibited significantly higher muscle strength than the non-obese group. However, when the measures of muscle strength were expressed as a percentage of body mass, the morbidly obese group exhibited a notable drop in strength per unit body mass as compared to the non-obese group. These results are consistent with those of previous studies, and again suggest that the presence of greater body mass counteracts the associated increase in absolute muscle strength with obesity.

In 2001, Hulens et al. investigated the effects of obesity on peripheral muscle strength, particularly isometric handgrip and isokinetic leg and trunk muscle strength, in women. They used an allometric approach which is designed to provide the most appropriate comparisons

between groups by providing results on a per ratio standard. In this case Hulens and colleagues standardized strength measures to a body size adjusted index based on free-fat mass. This was novel because it addressed the issue of confounding geometry between comparisons of obese and non-obese groups. Also controlling for age, physical activity, and height, Hulens et al. were able to determine that there was an increase in absolute strength, strength measures independent of body size, and power of muscles between the obese and non-obese subjects. Based on their results, it was proposed that a reduction in relative strength observed in the obese was indicative of impaired muscle function, rather than reduced physical activity (Hulens et al. 2001).

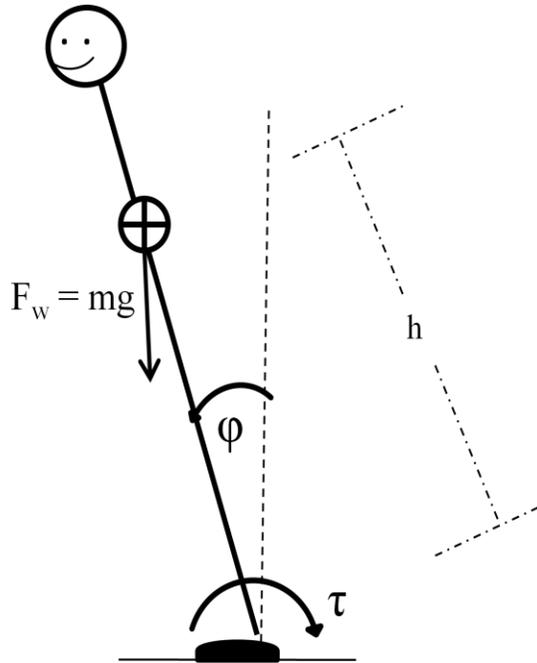
In order to further understand the relationship between obesity and muscle strength, Sartorio et al. (2005) investigated the changes in body composition, muscle strength, and power output after a multidisciplinary weight loss intervention in 95 obese men and women. Using a three-week body weight reduction program entailing dieting, moderate physical exercise, nutritional education, and psychological counseling as described by Maffiuletti et al. (2005), they found significant increases in isotonic measures of absolute strength and in the maximum leg power output per unit of body weight. Taken together, these results provide evidence that weight loss interventions both increase muscle strength relative to body weight (Sartorio et al. 2005) and increase balance recovery ability (Maffiuletti et al. 2005) thereby combining to decrease the propensity for falls.

### **C. Ambiguous Effects of Obesity on Balance Recovery**

While extensive research has been conducted on the effects of obesity on postural sway during quiet standing and on muscle strength, very little has been published on the effects of obesity on balance recovery. While the studies of quiet standing may be able to indicate an increased risk of falls there have been no published studies that directly investigate the effects of

obesity on balance recovery in the obese. For this reason, the obese effects on dynamic balance recovery are largely unknown.

A mechanics analysis based on the modeling of the body as an inverted pendulum leads to several theoretical implications about the effects of obesity on balance recovery. The inverted pendulum model of the body has been used extensively in studies investigating the control of postural sway in healthy adults (Winter et al. 2001, Bottaro et al. 2005) and to study balance recovery using an ankle strategy (Corbeil et al. 2001, Bogert et al. 2002, Robinovitch et al. 2002). The inverted pendulum model represents the body as a rod with the mass of the body concentrated at a point located at the center of mass (Figure 1.1). This simple model of the human body uses ankle joint torque as the only corrective torque used by the body to recover after a perturbation. This has been shown to be an appropriate assumption in prior research on gait characteristics of the obese (DeVita and Hortobagyi 2003).



**Figure 1.1. Inverted pendulum model showing the concentrated body mass located at the center of mass (COM), body weight ( $mg$ ), the height ( $h$ ) of the COM, angle away from upright ( $\phi$ ), and the ankle joint torque ( $\tau$ ).**

We know from the angular momentum equation of motion that,

$$\sum(\tau) = I\alpha \quad (1)$$

where  $\sum(\tau)$  is the sum of the torques,  $I$  is the moment of inertia about the pivot, and  $\alpha$  is the angular acceleration of the body. For our inverted pendulum we apply (1) about the ankle so that the torque due to body weight ( $F_w$ ) and the ankle joint torque are the only torques being applied to the system. The moment of inertia of the point mass is simply the mass of the body,  $m$ , times the distance away from the ankles,  $h$ , squared such that  $I = mh^2$ .

This simple model can be used to illustrate how obesity could potentially impair or enhance an individual's balance recovery ability. One argument that obesity can enhance balance recovery is based on the inertial effects of increasing body mass. With increased body

mass (i.e. large  $m$ ) there is an increase resistance to change in velocity/acceleration as evidenced by Newton's second law that  $F = ma$ . As the magnitude of the mass is increased, the associated force required to move that mass to a new state must also increase. By this reasoning, it can be inferred that for a given force perturbation, an obese person would experience a smaller displacement than a non-obese person due simply to their greater body mass and associated inertia. This supports the argument that obese individuals are less likely to be perturbed from their equilibrium position and therefore less likely to fall.

We can also see, however, from this investigation of inertia that were there to be a sufficiently large enough position perturbation to significantly displace the center of mass away from equilibrium (i.e. large  $\phi$ ) that the inertia of the obese person would tend to perpetuate the fall and would accordingly require a much larger ankle torque to correct the motion than would a non-obese person in the same situation. Therefore, the same obesity-based increase in inertia that supported the previous theory that obesity was beneficial to balance recovery is now used as evidence that obesity is inhibitory to balance recovery. This idea, however, could also be argued against by referencing the previously discussed results that found an increase in absolute muscle strength in obese adults. It could be argued that the displayed increase in muscle strength, particularly at the ankle joint, is used by obese adults to correct for the inertial effects of the trunk once in motion.

This investigation of the obesity effects on an inverted pendulum model of the body illustrates the ambiguous effects of obesity on balance recovery. In the literature on quiet standing the effect of increased obesity may not necessarily be fully described as the displacement from equilibrium is relatively small (i.e. small  $\phi$ ). For this reason, further research is needed to directly investigate the indefinite effect of obesity on balance recovery.

### **III. Introduction to Study**

The study of this thesis was developed to address the lack of information on the effects of obesity on dynamic balance recovery, particularly from a forward fall. While measures of balance during quiet standing and/or one-legged balance have been associated with risk of falls (Wallace et al. 2002), they have shown little association with the ability to recover balance from a postural perturbation (Wearing et al. 2006). This is important because the effects of obesity on balance are unknown during recovery from a postural perturbation. We know that controlling trunk movement during balance recovery from a postural perturbation is important (Pavol et al. 2001), and that the preferential accumulation of fat in the abdomen in the obese may increase the biomechanical demands of controlling trunk movement. However, no studies to our knowledge have investigated the effects of obesity on balance recovery from a large postural perturbation. Therefore, the first objective of this study was to determine the effects of obesity on balance recovery.

We also sought to investigate the effect of lower strength relative to body mass in obese individuals on balance recovery from a forward fall. We hypothesized that the decrease in strength relative to body mass may lead to obese individuals using greater relative effort (strength expressed relative to maximum available strength) during many tasks. Increased relative effort in the obese during balance recovery from a postural perturbation may explain any decrease in balance recovery ability in the obese. Investigating relative effort during balance recovery from a postural perturbation may help to elucidate why obese individuals are at an increased risk of falling. Therefore, the second objective of this study was to investigate the effects of obesity on relative effort in the lower extremities during balance recovery.

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## CHAPTER 2

### EFFECTS OF OBESITY ON SINGLE STEP BALANCE RECOVERY FROM A FORWARD FALL

#### **I. Introduction**

One of the most significant epidemiological trends of the last 20 years is the increased prevalence of overweight and obesity. Since 1980, the prevalence of adult obesity in the United States has doubled, and the prevalence of childhood overweight has tripled (Flegal et al. 2002, Ogden et al. 2002, Hedley et al. 2004). More recently, the prevalence of adult obesity in the US has grown from 27.5% in the years 1999-2000 to 31.1% in 2003-2004 (Ogden et al. 2006). As a result of this trend, the World Health Organization has characterized one billion individuals world-wide as being overweight or obese (Puska et al. 2003).

The high prevalence of obesity is problematic because obesity is associated with numerous medical conditions including an increased risk of falling (Lord et al. 1991, Lord et al. 1993, Baloh et al. 1995). In support of this, a small number of biomechanical studies have reported increased postural sway during quiet standing in the obese compared to non-obese (McGraw et al. 2000, Goulding et al. 2003). In addition, Maffiuletti et al. (2005) reported a shorter one-legged stance time in the obese. While measures of postural sway during quiet standing and/or one-legged balance have been associated with risk of falls (Hue et al. 2007), they have shown little association with the ability to recover balance from a postural perturbation (Owings et al. 2000). This is important because the effects of obesity on balance may be more pronounced during recovery from a postural perturbation. For example, an important sub-task during balance recovery from a postural perturbation is controlling trunk movement (Pavol et al. 2001). The preferential accumulation of fat in the abdomen in the obese may increase the

biomechanical demands of controlling trunk movement. No studies to our knowledge have investigated the effects of obesity on balance recovery from a large postural perturbation. Therefore, the first objective of this study was to determine the effects of obesity on balance recovery.

Muscle strength is thought to play an important role in balance recovery from a large postural perturbation (Lipsitz et al. 1994). Hulens et al. (2002) reported that obese adults exhibit greater lower extremity strength compared to non-obese adults, but lower strength when strength is expressed as a percentage of body mass. This lower strength relative to body mass may lead to obese individuals using greater relative effort (strength expressed relative to maximum available strength) during many tasks. Increased relative effort in the obese during balance recovery from a postural perturbation may help to explain any decrease in balance recovery ability in the obese, which, in turn, may help to elucidate why obese individuals are at an increased risk of falling. Therefore, the second objective of this study was to investigate the effects of obesity on relative effort in the lower extremities during balance recovery. It was hypothesized that obese adults would exhibit reduced balance recovery ability and increased relative effort during balance recovery compared to the non-obese.

## **II. Methods and Procedures**

### ***Participants***

Sixteen adults participated, including eight obese (three females and five males) of mean ( $\pm$ SD) age  $64.9 \pm 5.4$  years (mass =  $83.26 \pm 15.0$  kg, height =  $166.6 \pm 9.3$  cm, BMI =  $33.2 \pm 2.4$ ) and eight age and gender matched non-obese (age =  $64.0 \pm 6.4$ , mass =  $80.14 \pm 13.1$  kg, height =  $169.4 \pm 7.8$  cm, BMI =  $24.8 \pm 1.8$ ). Inclusion criteria required that all participants be free of

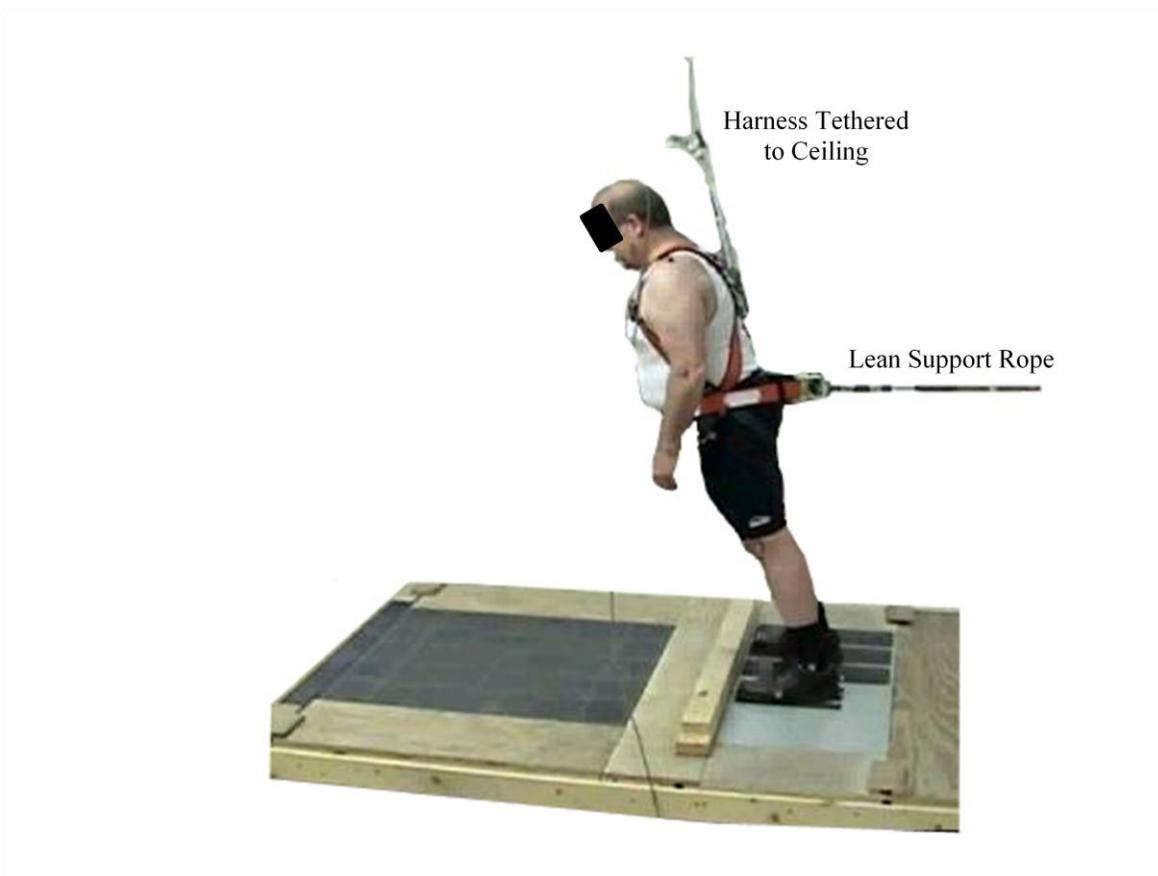
musculoskeletal injury and pass a medical screening performed by an internist to rule out individuals with any cardiac, respiratory, neurological, ontological, or musculoskeletal disorders, or a history of repeated falls. The study was approved by the Institutional Review Board at Virginia Polytechnic Institute and State University, and all participants provided written informed consent prior to the start of the study.

### ***Protocol***

The experimental protocol was adapted from Madigan and Lloyd (2005). Forward falls were induced by releasing participants from a static forward-leaning position. After release, participants attempted to recover their balance using a single step of the right leg. Successful recoveries were followed by another trial at a larger lean angle, and failed recoveries were followed by another trial at the same lean angle. This process was repeated until the participants failed to recover their balance twice at the same lean angle. Balance recovery ability was quantified by the maximum lean angle from which participants were able to recover using a single step. In addition to these lean trials, a battery of isometric muscle strength tests were performed to measure the maximum ankle plantar flexion, knee extension, and hip extension isometric joint torques of the right lower extremity. These data were used to quantify relative effort during balance recovery by expressing lower extremity joint torques as a percentage of their maximum isometric torque measure during strength tests.

To start each lean trial, participants stood with their feet shoulder-width apart and were leaned forward by only dorsiflexing at the ankle (Figure 2.1). Participants were held in this forward-leaning posture using a support rope spanning from the back of a belt to a releasable clasp affixed to a stable wooden structure. The lean angle was measured using a protractor located at the ankle and was adjusted by varying the length of the lean support rope. Participants

were asked to equally distribute their weight across both feet while maintaining heel contact with the ground and to keep their arms at their sides throughout each trial. A 7.5cm high obstacle was positioned in front of the participants to elicit a stepping response over the obstacle similar to that after a trip. After the participants were in position at the correct lean angle, they were verbally reminded to take a single step with their right foot for recovery. Participants were then released without warning 0-30 seconds after this verbal reminder. The initial lean angle was  $10^{\circ}$ , and the lean angle was increased by  $5^{\circ}$  after each successful recovery. In the event of a failed recovery, falls to the ground were prevented using a full-torso harness tethered to a ceiling-mounted support track with a fall-prevention lanyard. Violation of any one of three criteria were used to define a failed recovery: 1) when more than one step was taken with the right foot, 2) when a force greater than 30% of body weight was applied to the harness at any point during recovery, and 3) when the left foot crossed over the obstacle.



**Figure 2.1. Experimental setup for single-step recovery from a forward fall. The participant attempted to recover balance with a single step upon release of the lean support rope. The harness tethered to the ceiling prevented a fall to the ground in the event of an unsuccessful balance recovery.**

### *Data Collection and Analysis*

Body segment positions during each lean trial were sampled at 100 Hz using a Vicon 460 motion analysis system (Vicon Motion Systems Inc., Lake Forest, CA, USA). Reflective markers were placed on the right side of the body at the fifth metatarsal head, calcaneus, lateral malleolus, lateral femoral epicondyle, greater trochanter, and acromion process. Marker data were low-pass filtered at 7 Hz (second order zero-phase-shift Butterworth filter). Ground reaction forces in the stepping leg after heel contact were sampled at 1000 Hz using a force

platform (Bertec Corporation, Columbus, OH, USA) and subsequently low-pass filtered at 10 Hz (fourth order zero-phase-shift Butterworth filter). Harness load cell (Cooper Instruments & Systems, Warrenton, VA, USA) data was collected at 1000 Hz and subsequently low-pass filtered at 10 Hz (fourth order zero-phase-shift Butterworth filter).

To estimate sagittal plane joint torques in the stepping leg, the body was modeled as a two-dimensional system of four rigid body segments connected by frictionless pin joints. These segments represented the right foot, right shank, right thigh, and a head/arms/trunk (HAT) segment. The mass and inertial characteristics of the body segments were defined using published anthropometric relations (Pavol et al. 2002). Sagittal plane joint torques at the right ankle, knee, and hip were calculated using the inverse dynamics approach described by Winter (1990). Previous research (Madigan and Lloyd 2005) indicated the largest joint torques in the stepping leg during single step balance recovery from a forward fall occur during the support phase (i.e. the time interval between foot contact after stepping and the instant when both knee flexion velocity and HAT forward angular velocity reach zero). Peak joint torques were determined over this time interval. Joint torques during first 100ms after impact were not included in analysis to avoid artifacts due to impact with the ground.

To quantify relative effort, peak joint torques were expressed as a percentage of the maximum isometric torque measured during strength testing. Maximum isometric joint torque of the hip extensors, knee extensors, and ankle plantar flexors were measured at six equally spaced angles over each participant's full range of motion. During each test, torque and joint angle data were sampled at 200 Hz using a Biodex System 3 dynamometer (Biodex Medical Systems, Shirley, NY, USA) and subsequently low-pass filtered at 5 Hz (fourth order zero-phase-shift Butterworth filter). Body segment gravitational torques were subtracted from the

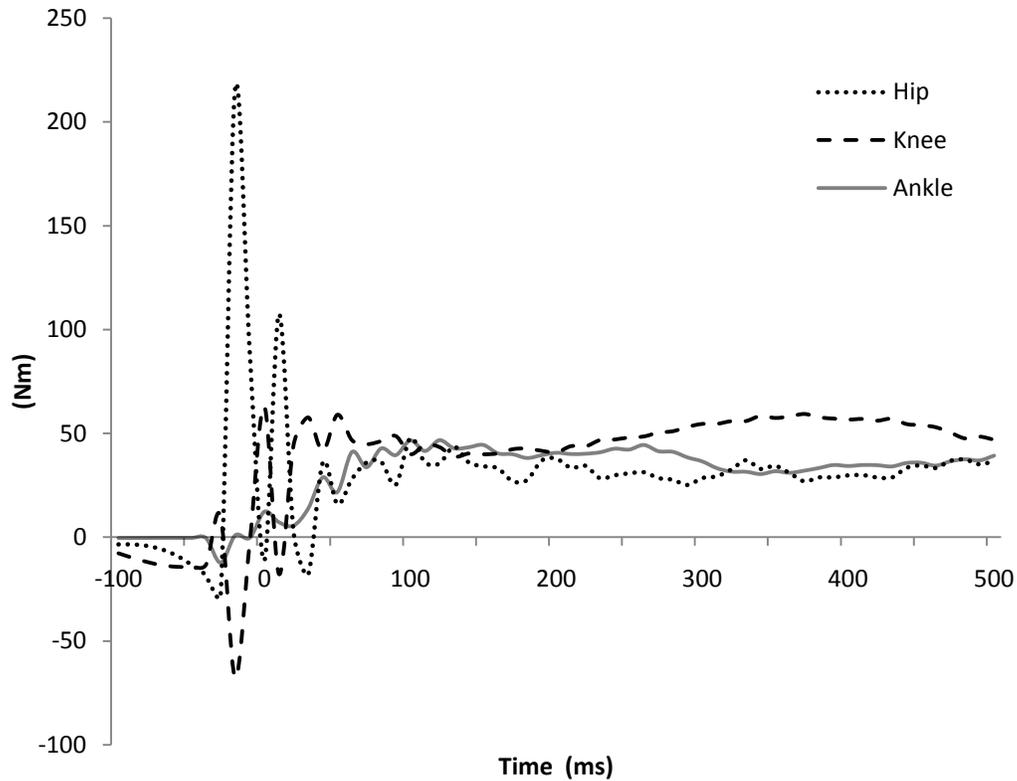
dynamometer torque signal to measure isometric joint torque. Peak relative effort was calculated by dividing the peak joint torque during balance recovery by the maximum isometric joint torque at the angle closest to the angle at which the peak joint torque during balance recovery occurred.

### ***Statistical Analysis***

An independent-sample *t*-test was used to investigate differences in maximum lean angle between the obese and non-obese. In addition, independent *t*-tests were used to investigate differences between the obese and non-obese in peak joint torque and relative effort during balance recovery at the 15° lean angle. Results were significant when  $p \leq 0.05$ . Statistical analyses were conducted using JMP IN 5.1.2 (SAS Institute, Cary, NC, USA).

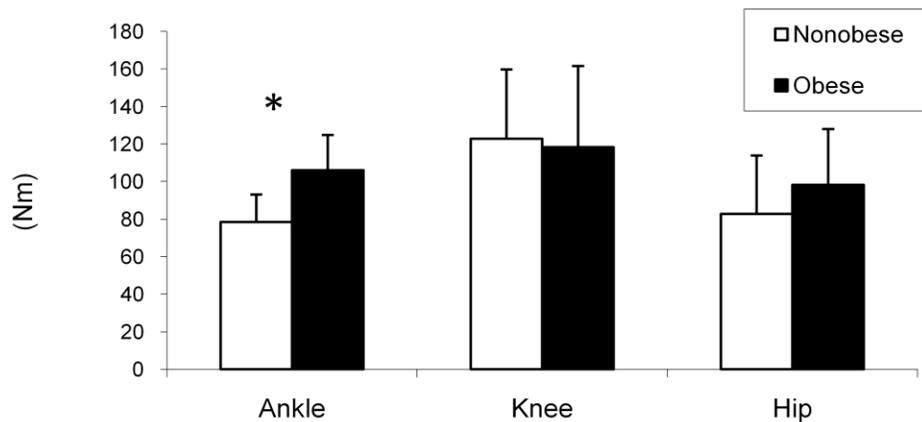
### **III. Results**

The obese achieved a smaller maximum lean angle than the non-obese ( $13.75 \pm 3.54^\circ$  vs.  $18.13 \pm 2.59^\circ$ ,  $p = 0.024$ ). A relatively consistent pattern of joint torques emerged for all participants during the support phase of balance recovery. Hip, knee, and ankle torques were predominantly extensor (or plantar flexor) throughout support phase of balance recovery (Figure 2.2).



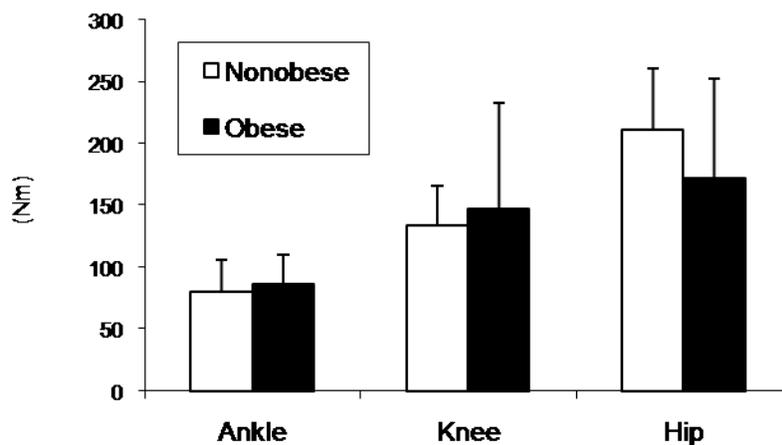
**Figure 2.2. Representative joint torques from an obese participant during balance recovery after release from a 15° lean angle. Time zero corresponds to foot impact, or the start of the support phase of balance recovery. Positive torque values correspond to extensor (or plantar flexor) torques.**

No differences in peak hip and knee extension torques were found between obese and non-obese (Figure 2.3), but peak ankle plantar flexion torque was higher in obese compared to non-obese ( $p = 0.035$ ).



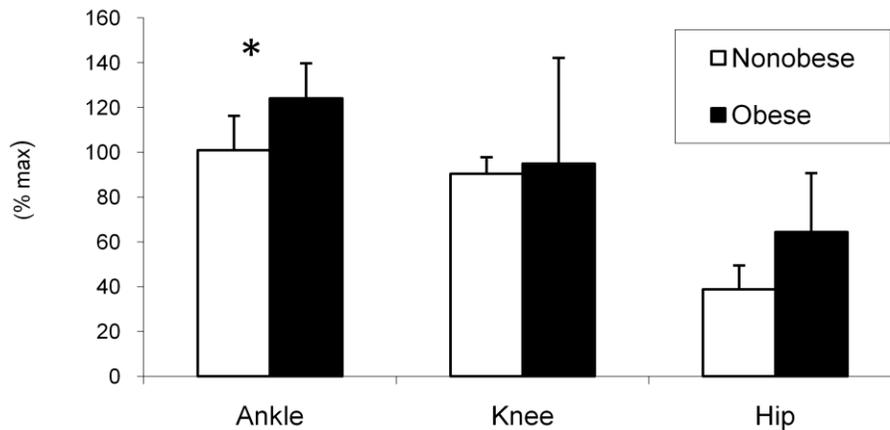
**Figure 2.3. Peak extensor torques during balance recovery after release from a 15° lean angle. \* indicates  $p < 0.05$ .**

Peak isometric torques during strength testing exhibited no differences between obese and non-obese (Figure 2.4).



**Figure 2.4. Maximum isometric joint torques during strength testing for both obese and non-obese participants. Each maximum was chosen from six isometric joint torques at joint angle most near measured angle of peak joint torque during balance recovery.**

No significant difference in peak relative effort at the knee were found between obese and non-obese, but similar to joint torques, relative effort at the ankle was higher in the obese compared to non-obese ( $p = 0.035$ ). There was an increase in hip extensor relative effort which approached statistical significance ( $p = 0.0957$ )



**Figure 2.5. Peak relative effort during the support phase of balance recovery after release from a 15° lean angle. \* indicates  $p < 0.05$ .**

#### **IV. Discussion**

The purpose of this study was to investigate the effects of obesity on balance recovery from a forward fall. Obese participants exhibited a smaller maximum lean angle, suggesting a reduced capacity to recover from a forward postural perturbation. In addition, obese participants exhibited larger peak ankle joint torque and relative effort during balance recovery. Post-hoc power analysis for the peak relative hip torque indicated a power of 0.57, and that the inclusion of three additional subjects in each group would have been sufficient to cause the measured differences to be statistically significant. We therefore attribute greater emphasis to the increase in the hip extensor relative effort in the obese participants than the statistical results would

indicate. Taken together, these results suggest that the decrease in maximum lean angle in the obese group may have resulted, at least in part, to the increase in relative effort in the obese.

Our results showed that the obese were not stronger than the non-obese. Previous studies have reported that obese adults typically possess greater strength than non-obese adults (Kitagawa et al. 1978, Lafortuna et al. 2005). Maffiuletti et al. (2007), for example, found that obese subjects displayed a 20% higher absolute muscle torque than non-obese subjects during tests of maximum voluntary isokinetic and isometric knee joint torque. Our results also showed that the obese group performed balance recovery with higher relative effort at the hip and ankle. Other studies have reported decreases in muscle strength when adjusted for body weight in the obese (Blimkie et al. 1990). Together, these findings suggest that relative effort, whether relative to body weight or maximum strength, may be a limiting factor to successful balance recovery in the obese.

Controlling and decelerating the trunk segment is critical during balance recovery from a postural perturbation (Pavol et al. 2001). The presumed higher trunk mass in obese individuals can make this more challenging due to higher gravitational and inertial loads required. Perhaps for this reason, DeVita and Hortobagyi (2003) found that obese participants, with approximately 80% more mass than non-obese, had larger ankle torque and power than non-obese participant when walking at similar speeds. It is interesting to note that the calculated differences in joint torques between the obese and non-obese were only significant at the ankle rather than at the hip or knee which are closer anatomically to the trunk. However, the increase in ankle extension (plantar flexion) joint torque calculated during the support phase of balance recovery for the obese participants indicate that it served to decelerate the forward motion of the trunk and to

assist in resisting the buckling of the stepping leg (i.e. decelerating hip flexion, knee flexion, and ankle dorsiflexion) (Madigan and Lloyd, 2005).

Several limitations of this study warrant discussion. First, it should be noted that several of the relative effort measures were above the theoretical maximum value of 100%. We feel this can be attributed to some participants giving sub-maximal effort during the strength tests. It should also be noted that using isometric strength tests to estimate relative effort does not account for variations in joint torques with joint angle and velocity (Sale et al. 1982, Westing et al. 1990). In addition, two joint muscles may induce further variation as in our analysis we matched only knee joint angle between tasks rather than both joints that these muscles cross. Second, although this analysis focused on sagittal plane joint torques, successful balance recovery also requires sufficient joint torques in other anatomical planes. Third, unlike outside of the laboratory, subjects were expecting a fall during the experimental protocol. We feel, however, that balance recovery ability in our study was mostly a function of participant physical performance capabilities which would not be expected to differ whether falls were induced expectedly or unexpectedly.

In conclusion, obese participants exhibited a poorer ability to recover from a forward fall with a single step, and this poorer ability may be related to increased relative effort during balance recovery. A growing number of epidemiological studies are reporting an increase in risk of falls in the obese (Wallace et al. 2002). The results from this study provide empirical evidence to support this epidemiological evidence, and information on the mechanisms that may contribute to this increased risk.

## **V. Acknowledgements**

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