EFFECTS OF OBESITY ON BALANCE RECOVERY IN RESPONSE TO SMALL POSTURAL PERTURBATIONS

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Abstract

Obesity is a major and growing health concern associated with an increased risk of falls. The majority of falls are thought to result from some kind of postural perturbation, yet the biomechanical mechanisms as to why obese individuals fall more often is unclear. Therefore, the goal of this study was to investigate the effects of obesity on balance recovery in response to small forward postural perturbations. Twenty male participants, including 10 lean (mean BMI ± SD: 21.9 ± 1.4) and 10 obese (BMI: 33.2 ± 2.3), were exposed to two types of postural perturbations (force impulses applied with a pendulum and angular displacements administered with a release mechanism). Participants attempted to recover balance with only an ankle strategy such that neither a step nor hip flexion was utilized. Quiet standing trials were also conducted for comparison with the literature. Obese individuals exhibited less center of mass (COM) displacement and a slower COM velocity compared to lean individuals when exposed to identical force perturbations. When exposed to the force perturbations relative to body weight, and when released from identical lean angles, no differences in COM performance were found. During quiet standing, no differences in center of pressure (COP) velocity were observed between obese and lean groups. In all tasks, the obese generated higher ankle torque than the lean. Overall, the obese participants exhibited no differences in movement or less/slower movement than the lean participants when recovering from small forward postural perturbations as well as during quiet standing. These results imply that obesity in young adult males did not impair balance recovery for the tasks investigated.

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Chapter 1 - Introduction

Obesity as a Public Health Problem and Economic Issue

Over the past three decades, the prevalence of obesity in the United States among adults aged 20-74 has more than doubled from 15% to 32.2% while overweight prevalence among children and adolescents aged 2-19 has more than tripled from about 5% to 17.1% [1-5]. The World Health Organization estimates that more than one billion people worldwide are overweight, and of these, 300 million are obese [6]. This high prevalence is problematic because obesity is associated with numerous health problems including heart disease, diabetes, cancer, and breathing problems [7] as well as increased mortality [8]. Disabling musculoskeletal conditions are also related to obesity. A few of these include low back pain, osteoporosis, fibromyalgia, gait disturbance, and osteoarthritis [9, 10]. Due to the high prevalence of obesity and its associated debilitating conditions, obesity also poses a major health care and economic issue [7, 11, 12]. Costs attributed to obesity in the United States rose from $99.2 billion in 1995 to $117 billion in 2000 [7, 12].

Obesity and Falls

Middle-aged and older obese adults fall almost twice as frequently (27%) as their lean counterparts (15%) per year [13]. In addition, the odds of a fall-related injury requiring medical treatment are 15%-79% higher for those that are overweight, obese, or morbidly obese [14]. Injuries such as sprains, strains, and dislocations in the obese are more frequently due to falls and are the main types of injury-related hospitalizations

compared with non-obese persons [15]. Obesity increases an individual's risk for

multiple falls, which is also related to higher fracture risk [16]. Similarly, it was found

that the risk of major injury (fracture, dislocation, or laceration requiring suture) per fall

was increased in previously fractured individuals [17]. A higher fracture risk could

therefore increase obese individuals' risk of incurring multiple major injuries.

Musculoskeletal Impairments in the Obese

Abnormal and impaired musculoskeletal functions observed in the obese are known to

be strong indicators of fall risk [18]. For example, decreased muscle forces are related

to an increased number of falls [19-21]. Therefore, lower-extremity muscle function

impairments could put the obese in association with fall risk. While obese individuals

typically exhibit increased muscle strength compared to lean individuals [22-25], they

are not as strong relative to their mass [23, 24, 26]. Absolute strength of the knee and

trunk extensors and oblique abdominals in obese individuals is reported as being higher

than that in non-obese individuals [23]. However, when expressed relative to body

mass, strength is less in the obese for knee and trunk extension, oblique abdominal

contraction, and hand gripping [23]. Similarly, the obese have greater absolute but

lower mass-relative torque and power in the quadriceps muscles [24]. This same study

observed increased fatigue, another characteristic of weak muscles in the obese

compared to the lean. Fatigue was determined with a measure of decreased voluntary

torque generation over time. One study went a step further, not only measuring

strength during knee extension, but also motor unit activation as a percentage of muscle

cross-sectional area in response to electrical stimulation. It was determined that mass-

relative torque was again lower in the obese, and they exhibited a decreased percentage of twitch torque response [26]. A lack of muscle activation capacity and decreased relative strength limit muscle function in the obese, putting them at a greater risk for falling.

Decreased sensorimotor functioning in the obese could degrade control of postural balance and balance recovery, causing an increased number of falls. Foot proprioception strongly influences postural balance control as well as some types of postural responses to perturbations [27-29]. Obese subjects, compared to lean, showed increased plantar pressures (in general and underneath the forefoot) as well as larger forefoot width and plantar ground contact area during standing and walking [30-32]. Higher plantar pressures can cause pain [33] and tissue damage [34], suggesting a reduction in proprioception within the foot pad beneath the bones of the feet, making it harder to sense the need for postural and gait corrections. Obesity is also linked to increased sensory thresholds in all nerves due to a metabolic alteration that could lead to peripheral neuropathy [35]. This condition affects proprioception even without the addition of external pressure. Decreased proprioception in the obese could hinder balance control, increasing their risk of falls.

Another impairment associated with obesity is knee osteoarthritis [36] which involves joint weakness, another particular fall risk [20]. A weight loss intervention within obese osteoarthritic patients showed reductions in compressive and resultant knee forces as well as knee abduction moment during gait [36]. Similarly, exercise and diet

interventions resulted in improvements in physical function, disability, and pain due to strength gains and weight loss in obese osteoarthritic patients. In one study, exercise alone facilitated weight loss and improved disability, knee pain, and physical performance [37]. Adding dieting into the regimen showed those same improvements as well as increased weight loss and improved gait parameters (e.g. increased loading rate and maximum braking force). A similar study saw improved 6-minute walk performance with exercise alone and additional improvements of increased physical function as well as decreased weight, stair time, and knee pain due to exercise and diet together [38]. Diet alone revealed only weight loss without any of the functional improvements or pain reductions. It can be thought that these improvements within obese osteoarthritic patients can be translated to the obese population since most of the symptoms of osteoarthritis are brought on by and shared with obesity. If obese osteoarthritic patients can improve their functioning, obese individuals without osteoarthritis should be able to as well.

Posture and Gait in the Obese

Impaired musculoskeletal functions in obese individuals, along with the need to support increased body weight, can result in modifications to posture. Many of these modifications have been associated with a risk of falls [18]. Morbidly obese individuals have posture deviations resulting from and compensating for excessive weight overload. These deviations include scoliosis, kyphosis, and hyperlordosis of the spine as well as anteversion and lateral version of the head, unleveled shoulders and hips, and a wider base of support [39]. While a wider stance aids in a greater control of

balance, it can lead to valgum knees and external deviation of the shanks and feet [39].

The wider stance and external deviation are caused by larger thighs and shanks [40]

physically forcing abduction of the lower extremities, and as the legs spread, the hips

naturally rotate (i.e. causing eversion) for a more comfortable and stable progress. The

obese also exhibit more trunk extension while standing [41] which can be interpreted as

a strategy for counteracting an increased anteriorly displaced center of mass (COM) as

seen in the obese [42]. During a standing work task, obese individuals perform with a

more flexed trunk posture and increased hip extensor moment than lean individuals

[41]. Since the task involves trunk flexion in itself, that same anteriorly displaced COM

in the obese could be pulling the trunk forward even more making increased hip

extensor moment necessary for support.

Impaired musculoskeletal functions in the obese also result in gait modifications related

to fall risk [18]. In self-paced walking, as well as slower speeds, obese individuals

exhibit shorter stride lengths, wider step widths, and an increased variation of hip

abduction throughout the gait cycle [43]. A wider step width again is due to larger thighs

and shanks as well as implementing a balancing strategy. However, using wider step

widths while walking can induce an increased metabolic cost [44] which could cause

premature fatigue and increase chances for injury.   An inclination for fatigue could be

hazardous because it has proven to cause decreases in postural control and increases

in attention demands [45, 46], both of which could lead to falls. Obesity is also related

to longer stance phases and shorter swing phases while walking [47], similar to the way

the elderly adapt to their own diminishing abilities which are highly attributed to

decreased strength and diminished balance [48]. These gait adaptations in the obese

suggest an attempt at a more stable walking strategy. While walking at a self-selected

speed, obese individuals have been observed to exhibit greater knee and ankle

extension compared to lean individuals [49]. Walking at a standardized speed, they

exhibit greater joint extension in all lower extremity joints (the hip, knee, and ankle) [49].

This erect posture adaptation for maintaining walking balance follows the same idea of

counteracting an increased anteriorly displaced COM, even more so at a standardized

speed. Other characteristics of gait in the obese involve altered foot mechanics. They

include a greater eversion angle, larger total eversion range of motion, faster maximum

eversion velocity, and increased forefoot abduction, all resulting in greater rearfoot

motion [50]. These characteristics expand on how the obese attempt to form a more

stable base for supporting extra mass while in motion.

Obesity and Balance

Standing balance in the obese appears to be hindered, and adequate balance is

necessary for fall prevention [51]. Increased postural sway during quiet standing is

considered an accepted measure of decreased balance capabilities (i.e. less sway

movement would provide a greater margin of safety with respect to base of support

boundaries). A few studies have reported increased postural sway with increased

weight in young and middle-aged adults during quiet standing [52-54]. In particular,

obese individuals are associated with an increased center of pressure (COP) range

[54], sway area [55], and velocity [53, 54]. Increased COP velocity has been associated

with a risk of falling in older adults [56, 57], and it suggests that obese control may be

more abrupt and less fine-tuned due to an increased need for postural corrections. In contrast, studies mainly investigating plantar pressures underneath the feet observed no effects of obesity on COP displacements in young or middle-aged adults during quiet standing [30, 32]. Obesity in adolescents and older adults has also been linked to an inability to retain balance while voluntarily leaning forward and backward as far as possible with heels and toes remaining on the floor [58, 59]. While testing for obesity stability limits, it was also observed that decreased knee strength and increased pain associate with poorer dynamic balance [58]. In study conducted on males aged 10-21, a Bruininks-Oseretsky [60] sub-test of balance, consisting of 3 items of static balance and 5 items of dynamic performance balance on the floor and on a beam, revealed scores that were negatively correlated with body weight, body mass index (BMI), percentage fat, and total fat mass [61]. Obese boys aged 8-10 have been found to have increased peak COP displacements and sway areas during quiet standing [55]. However, studies on obese adolescents show that they have the same COP displacements and path lengths on a hard surface as the lean [59, 62] and increased COP path lengths only when on a foam surface [62]. The latter suggests a balance inability in the younger obese with increasing task difficulty. Joint/muscle function and individual morphology are categorized as main biomechanical factors involved in balance control [63]. Therefore, since decreased musculoskeletal function and altered posture and gait are exhibited in the obese, it makes sense that these hindered balance capabilities are also observed. All of these factors appear to contribute to the increased risk of falls in the obese.

The effect of body weight on balance can be revealed more clearly with results of intervention studies. Since balance is an underlying factor of fall prevention [51], beneficial interventions can be helpful for reducing fall risk in the obese. Many studies have shown improvements in balance due to weight loss in young, middle-aged, and older adults [54, 64, 65]. In particular, decreased postural sway was observed after weight loss in previously obese and morbidly obese subjects [54]. The obese patients adhered to hypocaloric diets, while the morbidly obese patients underwent bariatric surgery. Following the interventions, both groups dropped below an obese BMI of 30 kg/m^2, and their COP speeds and ranges decreased significantly. Likewise, body weight reduction can enhance time of balance maintenance and reduce trunk sway in obese and extremely obese individuals [64]. Weight loss here was attained with an energy-restricted diet, moderate physical exercise, nutritional education, and psychological counseling. Not all of the outcomes for this case can be attributed to weight loss alone because of the possible muscle and coordination enhancements, but it can be thought to contribute. In the same manner, interventions resulting in weight loss that separately involve weight training or aerobic exercise in osteoarthritic patient groups improved postural sway (i.e. reduced mean displacement and velocity, elliptical area, and increased balance time) [65]. Therefore, balance can be considered to be influenced by factors of body weight, muscle strength, and proprioception, all of which have been shown as disadvantageous in the obese.

Obesity and Balance Recovery

The majority of falls are thought to result from some kind of postural perturbation [66],

yet the biomechanical mechanisms as to why obese individuals fall more often is

unclear. Based on obese individuals exhibiting increased postural sway during quiet

standing, one may speculate that they also have an impaired ability to recover balance

from a postural perturbation. However, it has been shown that postural sway during

quiet standing is not necessarily associated with the ability to recover balance from a

postural perturbation [67, 68]. To our knowledge, no studies to date have investigated

the effects of obesity on balance recovery from an externally applied postural

perturbation. Yet, some studies have either simulated increased body mass with an

external perturbation or simulated an internal disturbance with actual obese and lean

subjects. For example, it was found that an external increase of body mass was

associated with larger displacements of COP during a load catching task [69]. Similarly,

randomized support surface perturbations caused those with an external increase of

mass to have increased sway areas [70]. When actual obese and lean subjects were

analyzed, increased forward COP displacement and speed were observed in obese

individuals when performing goal directed upper limb movements [71]. These

movements were described as eliciting a postural perturbation to the body, but the

results can only specifically suggest a constraint on balance in the obese while

executing upper body tasks. More work is necessary to fully understand the effects of

obesity on balance in response to an externally applied postural perturbation.

Multiple theoretical considerations of human balance using an inverted pendulum model

indicate a potentially ambiguous relation between obesity and balance and/or balance

recovery. First, increased body mass and an anteriorly displaced trunk COM with

respect to the spine due to a larger anterior abdominal mass [42] leads to an increased gravitational moment about the ankles for a given angular displacement from vertical. This would appear to challenge and/or impair balance recovery, especially in response to a forward perturbation. In fact, a mathematical model of balance recovery from a forward postural perturbation showed the need for increased ankle torque in the obese during recovery [42]. Second, increased body mass with obesity also leads to an increased mass moment of inertia about the ankles. It could be argued that this may provide a disadvantage to balance recovery when the body is already moving because it would be harder to slow down and return to equilibrium. Increased moment of inertia could alternatively provide a benefit to balance recovery after a force perturbation based upon the impulse-momentum relationship. If lean and obese individuals are exposed to the same external impulse perturbation, the increased body mass in the obese would result in a smaller increase in velocity, which may be easier to recover from before the COM leaves the base of support. Aside from the pendulum mechanics, another factor that likely affects balance recovery in the obese is strength. While obese individuals typically exhibit increased muscle strength compared to lean individuals, they are not as strong relative to their mass [24]. This may impair balance recovery capability in the obese. Based upon these considerations, the effects of obesity on balance recovery are equivocal.

Purpose

The goal of this study was to investigate the effects of obesity on balance recovery in response to small forward postural perturbations. Small perturbations that did not

require a stepping response were investigated so that results could be interpreted with

regard to the inverted pendulum considerations. Forward perturbations were

investigated based upon the expectation that the anteriorly displaced trunk COM in the

obese would make them more susceptible to imbalance after a forward perturbation.

Based upon increases in postural sway during quiet standing [53-55] and increased

torque requirements during balance recovery [42], it was hypothesized that obese

individuals would exhibit a diminished balance recovery capability compared to lean

individuals.

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Chapter 2 - Effects of Obesity on Balance Recovery

in Response to Small Postural Perturbations

Introduction

Over the past three decades, the prevalence of obesity in the United States (US) among

adults aged 20-74 has grown from 15% to 32.2% [1-4]. The US is not the only country

with an obesity concern. In fact, the World Health Organization estimates that more

than one billion people world-wide are overweight, and of these 300 million are obese

[5]. This is problematic because obesity is associated with numerous health problems

including heart disease, diabetes mellitus, and cancer [6]. In addition to these health

problems, epidemiological evidence suggests that obese individuals have a higher

incidence of falls (27% vs.15%) per year [7] and greater odds of sustaining a fall-related

injury [8] than non-obese individuals.

Consistent with an increased risk of falling, a few studies have reported increased

postural sway during quiet standing with increased weight [9-12]. In particular, obese

individuals are associated with an increased center of pressure (COP) range [11], sway

area [12], and velocity [10, 11]. Obesity has also been linked to an inability to retain

balance while voluntarily leaning forward and backward as far as possible [13]. In

another study, a Bruininks-Oseretsky [14] sub-test of balance, consisting of 3 measures

of static balance and 5 measures of dynamic balance on the floor and on a beam,

revealed scores that were negatively correlated with body weight, body mass index,

percentage fat, and total fat mass [15]. In addition to these cross-sectional studies,

intervention studies have shown that balance during quiet standing can improve with weight loss [11, 16, 17].

The majority of falls are thought to result from some kind of postural perturbation [18], yet the biomechanical mechanisms as to why obese individuals fall more often is unclear. Based on obese individuals exhibiting increased postural sway during quiet standing, one may speculate that they also have an impaired ability to recover balance after a postural perturbation. However, it has been shown that postural sway during quiet standing is not necessarily associated with the ability to recover balance from a postural perturbation [19, 20]. Moreover, multiple theoretical considerations of human balance using an inverted pendulum model indicate a potentially ambiguous relation between obesity and balance and/or balance recovery. First, increased body mass and an anteriorly displaced trunk center of mass (COM) with respect to the spine (due to a larger anterior abdominal mass) [21] leads to an increased gravitational moment about the ankles for a given angular displacement from vertical. This would appear to challenge and/or impair balance recovery, especially in response to a forward perturbation. In fact, a mathematical model of balance recovery from a forward postural perturbation showed the need for increased ankle torque in the obese in order to recover balance [21]. Second, increased body mass also leads to an increased mass moment of inertia about the ankles. This may provide a disadvantage to balance recovery when the body is already moving because it would be harder to slow down and return to equilibrium. Alternatively, increased moment of inertia could provide a benefit to balance recovery after an externally applied perturbation based upon the impulse-

momentum relationship. If lean and obese individuals are exposed to the same impulse from the perturbation, the increased body mass in the obese should result in a smaller increase in velocity. It may be easier to recover balance because this smaller velocity may assist in keeping the COM within the base of support. Aside from the pendulum mechanics, another factor that likely affects balance recovery in the obese is strength. While obese individuals typically exhibit increased muscle strength compared to lean individuals, the obese are not as strong relative to their body mass [22]. Since muscle weakness has been determined as an important risk factor for falls [23], this characteristic in the obese may impair balance recovery capabilities.

Due to these considerations, the effects of obesity on balance recovery are equivocal. Therefore, the goal of this study was to investigate the effects of obesity on balance recovery in response to small forward postural perturbations. Small perturbations that did not require a stepping response were investigated so that results could be interpreted with regard to the inverted pendulum considerations. Forward perturbations were investigated based upon the expectation that the anteriorly displaced trunk COM in the obese would make them more susceptible to imbalance following a forward perturbation. Based upon increases in postural sway during quiet standing [10-12] and increased torque requirements during balance recovery [21], it was hypothesized that obese individuals would exhibit a diminished balance recovery capability compared to lean individuals.

Methods

Twenty moderately active male participants, including 10 lean (mean BMI ± SD: 21.9 ± 1.4, age: 21 ± 2.1) and 10 obese (BMI: 33.2 ± 2.3, age: 22.7 ± 4.5), participated in this study. This study was approved by the Virginia Tech Institutional Review Board, and written consent was obtained from all participants prior to participation.

Balance recovery from two types of postural perturbations was investigated. Postural sway during quiet standing was also investigated for comparison with the literature. The first type of postural perturbation consisted of forward-directed force perturbations applied to the trunk using padded ballistic pendulums. These force perturbations, in effect, resulted in an initial angular velocity of the body from which balance was recovered with an ankle strategy (defined as recovering without stepping using only the ankle musculature and keeping body segments aligned). The second type of perturbation involved releasing participants from a static forward lean. These position perturbations resulted in an initial angular displacement of the body from which balance was recovered with an ankle strategy. Both force and position perturbations were investigated because the effects of obesity on balance recovery may differ between the two due to differences in the effective initial conditions.

Force perturbation trials began with participants standing quietly with feet together, hands clasped behind the back, head facing forward, and eyes closed (Figure 1). Perturbations were applied by pulling the pendulum away from the participants in the mid-sagittal plane and then releasing it. The padded end of the pendulum impacted

participants just inferior to the scapula [24]. The pendulum was pulled back a specified

distance prior to release to achieve the desired perturbation magnitude as defined by

the linear momentum immediately before impact. Four perturbations were applied at

magnitudes of 1, 2, 3, 4, 5, 6 and 8 N·s (mean impulse duration of ~180 ms), and

perturbations were presented in increasing order. Participants were instructed to keep

their ankles relaxed prior to perturbations and recover balance with an ankle strategy.

Backward perturbations were intermittently applied to prevent anticipation, but were not

included in the analysis. During all force perturbation trials, noise-cancelling

headphones were worn to prevent any auditory cues of an impending perturbation.
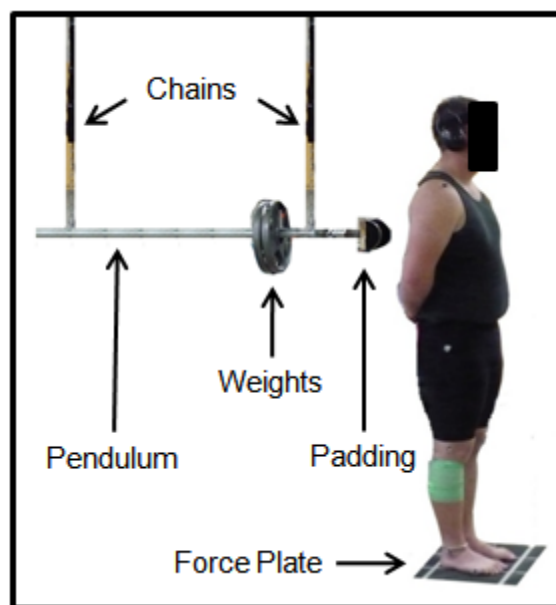

Figure 1: Experimental set-up of the pendulum force perturbations. A second pendulum, not
shown here, was positioned in front of the participant and used to apply intermittent backward
perturbations to help prevent anticipation of perturbation direction.

Position perturbation trials began with participants being held in a static forward lean

with their feet together, hands clasped behind the back, head facing forward, and eyes

open (Figure 2). Perturbations were applied by releasing participants from the forward

lean without warning. One perturbation was applied at increasing lean angles including

2, 2.5, 3, 3.5, and 4 degrees beyond the mean body angle during quiet standing. This

angle was measured between vertical and a line from the ankle to the greater trochanter

using a goniometer. Participants were instructed to keep their ankles relaxed prior to
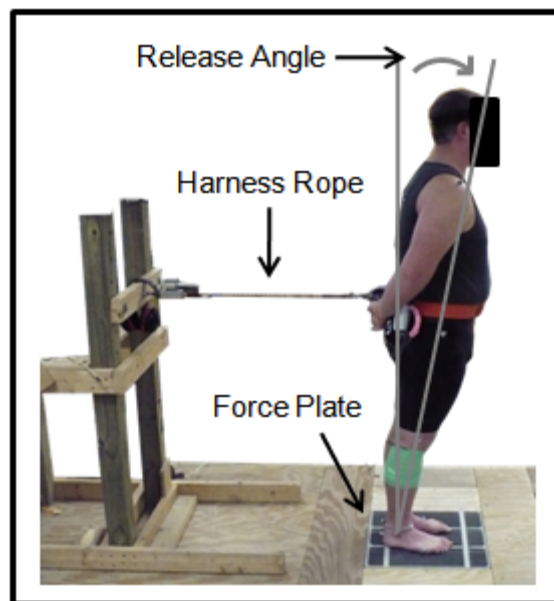
release and recover balance with an ankle strategy.

Figure 2: Experimental set-up of the release-from-lean position perturbations.

Eight quiet standing trials lasting 30 seconds each were also conducted. Participants

were instructed to maintain an upright stance for the duration of the trial while keeping

their feet together, hands clasped behind their back, and eyes open.

During all trials, ground reaction forces and moments were sampled at 1000 Hz using a

six degree-of-freedom force platform (Bertec Corporation, Columbus, OH), low-pass

filtered at 7 Hz (zero phase lag 4th order Butterworth), and downsampled to 100 Hz. Body position was sampled at 100 Hz using a Vicon 460 Motion Analysis System (Lake Forest, CA) and low-pass filtered at 5 Hz (zero phase lag 4th order Butterworth). Reflective markers were placed bilaterally on the temporal bone, acromion, greater trochanter, lateral femoral epicondyle, lateral malleolus, calcaneus, and the 5th metatarsal head. Pendulum impact forces were sampled at 1000 Hz using an in-line load cell (Cooper Instruments and Systems, Warrenton, VA), low-pass filtered at 20 Hz (zero phase lag 2nd order Butterworth), and downsampled to 100 Hz. Voltage data from the release mechanism used during the position perturbation trials was sampled at 1000 Hz, low-pass filtered at 20 Hz (zero phase lag 4th order Butterworth), and downsampled to 100 Hz.

During both force and position perturbation trials, peak anterior/posterior (A/P) COM displacement, COM velocity, and peak plantar flexor ankle torque were determined. The COM for each participant was found using a geometric anthropometric model [25]. To account for a potential anterior shift of the trunk COM as reported in obese individuals [21], which is not accounted for in this anthropometric model, the average A/P distance between the whole body COM and COP over eight 30-second quiet standing trials was determined. This distance was then used to offset the COM A/P position during all perturbation trials because it should theoretically equal zero over an extended period (COP continuously oscillates on either side of the COM during quiet standing). Peak sagittal plane ankle plantar flexor torque was calculated using the COP, ankle marker position (averaged across left and right sides), and an inverse

dynamics analysis. For the quiet standing trials, mean A/P COP velocity and peak

ankle plantar flexor torque were determined. Mean COP velocity was chosen because

it has been associated with a risk of falling in older adults [26, 27] and has been

observed to be increased in the obese [10, 11].

A 2-way ANOVA was used for the perturbation trials to investigate the effects of group,

perturbation magnitude, and their interaction on peak COM displacement, peak COM

velocity, and peak ankle torque. Separate ANOVAs were performed for force and

position perturbation trials. Pairwise comparisons following a significant interaction

were performed using Tukey's HSD. A secondary analysis was conducted on data from

the force perturbation trials after perturbation magnitudes were normalized by body

weight. One obese participant was not included in the position perturbation data at

levels greater than 3 degrees from standing posture due to an inability to recover

balance with the ankle strategy. Independent t-tests were used to investigate the

effects of group on mean COP velocity and peak ankle torque during quiet standing. All

statistical analyses were conducted using JMP 7 (Cary, North Carolina, USA) with a

significance level of p≤0.05.

Results

During force perturbation trials, peak COM displacement (Figure 3a) increased with

increasing perturbation magnitude (p<0.001) and was larger in the lean group compared

to the obese group (p<0.001). A group × perturbation magnitude interaction was found

(p=0.005), and pairwise comparisons indicated the lean group exhibited larger peak

COM displacement than the obese group at perturbation levels 5-8 N·s. Peak COM velocity (Figure 3b) increased with increasing perturbation magnitude ($p<0.001$) and was larger in the lean group compared to the obese group ($p<0.001$). A group × perturbation magnitude interaction was found ($p<0.001$), and pairwise comparisons indicated the lean group exhibited larger peak COM velocity than the obese group at perturbation levels 3-8 N·s. Peak ankle torque (Figure 3c) increased with increasing perturbation magnitude ($p<0.001$) and was larger in the obese group ($p=0.017$) compared to the lean group. There was no group × perturbation magnitude interaction for peak ankle torque. After normalizing the force perturbations by body weight, peak COM displacement (Figure 3d) and velocity (Figure 3e) increased with increasing perturbation magnitudes ($p<0.001$), but exhibited no effects of group ($p=0.431$ and 0.129, respectively) or group × perturbation magnitude interactions ($p=0.313$ and $p=0.840$, respectively). Peak ankle torque (Figure 3f) increased with increasing perturbation magnitude ($p<0.001$) and was larger in the obese group compared to the lean group ($p=0.003$). A group × perturbation magnitude interaction was also found ($p<0.001$) based upon a higher slope in the lean group.
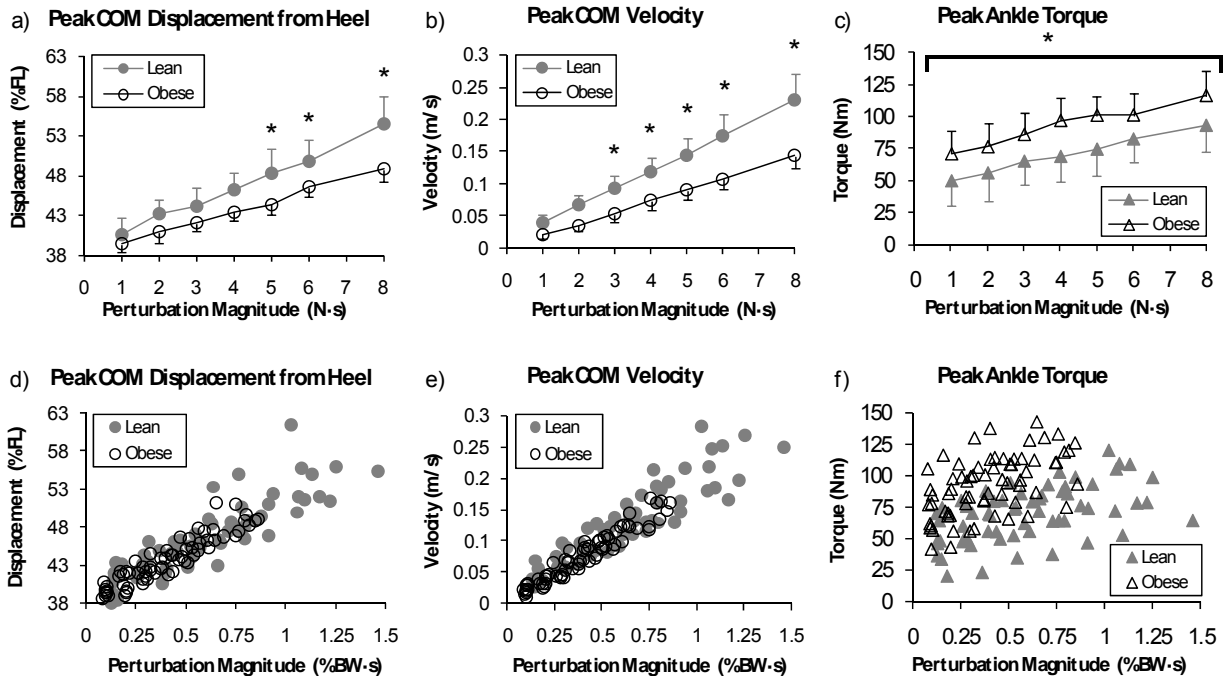
Figure 3: Results from force perturbation trials: a) Least squares means of peak COM displacement with set magnitude perturbations. b) Least squares means of peak COM velocity with set magnitude perturbations. c) Least squares means of peak plantar flexor torque with set magnitude perturbations. d) Peak COM displacement with perturbations normalized by participant body weight. e) Peak COM velocity with perturbations normalized by participant body weight. f) Peak plantar flexor torque with perturbations normalized by participant body weight. FL=Foot Length. An asterisk (*) indicates a significant difference between groups at the designated perturbation magnitude.

During position perturbation trials, peak COM displacement (Figure 4a) and velocity (Figure 4b) increased with increasing perturbation magnitude (p<0.001), but no effects of group (p=0.223 and p=0.451, respectively) were found. A group × perturbation magnitude interaction was not found for peak COM displacement (p=0.082), but was found for peak COM velocity (p=0.018) based upon a higher slope in the obese group (although no pairwise differences were found between groups at each lean angle). Peak plantar flexor ankle torque (Figure 4c) increased with increasing perturbation

magnitude (p<0.001) and was larger in the obese group compared to the lean group (p<0.017). A group × perturbation magnitude interaction was found (p<0.001), and pairwise comparisons indicated the obese group exhibited larger peak ankle torque than the lean group at 4 degrees from standing posture.
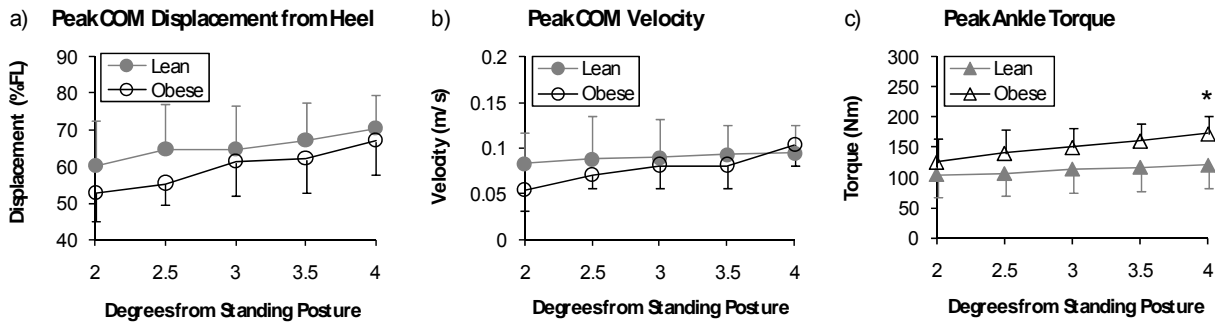

Figure 4: Results from position perturbation trials: a) Least squares means of peak COM displacement. b) Least squares means of peak COM velocity. c) Least squares means of peak plantar flexor torque. FL=Foot Length. An asterisk (*) indicates a significant difference between groups at the designated perturbation magnitude.

During quiet standing trials, mean COP velocity (Figure 5a) was not different between groups (p=0.389), but peak ankle torque (Figure 5b) was ~51% higher in the obese compared to the lean (p=0.012).

Figure 5: Results from quiet standing trials: a) Least squares means of mean COP velocity. b) Least squares means of peak plantar flexor torque. An asterisk (*) indicates a significant differerence between groups.

Discussion

The goal of this study was to investigate the effects of obesity on balance recovery in response to small forward postural perturbations. In general, obese individuals exhibited less and COM movement compared to lean individuals when exposed to identical small force perturbations. When exposed to the identical force perturbations relative to body weight, and when released from identical lean angles, no differences in COM movement were found. Obese individuals, in general, generated higher ankle torque than lean individuals in response to both types of perturbations. During quiet standing, no differences in mean COP velocity were found between groups, but the obese did exhibit increased ankle torque. Contrary to our hypothesis, and based upon the premise that less COM displacement and velocity provide a greater margin of safety with respect to the base of support boundaries, these results imply that obesity did not impair balance recovery for the tasks investigated.

Force and position perturbations trials were performed to explore how different initial conditions may influence balance recovery in the lean and obese. During force perturbation trials, participants were given an initial angular velocity resulting from an impulse exposed to the body at pendulum impact [28], while having a near-zero initial angular displacement from normal standing posture. During position perturbation trials, participants were given an initial angular displacement and no initial angular velocity. When exposed to identical force perturbations, obese participants experienced smaller initial angular velocities (not shown in results, but available upon request). This was expected based upon their larger body mass and the impulse-momentum relationship

[28].   A smaller initial velocity would seem to be more easily attenuated than the larger

initial velocity experienced by the lean, and this is supported by smaller peak COM

displacement and velocity in the obese (Figure 3a,b). When exposed to the identical

force perturbations relative to body weight, there were no differences in initial angular

velocities (not shown in results, but available upon request) and no differences in COM

kinematics between obese and lean participants (Figure 3d,e). Similarly, when exposed

to identical position perturbations, no differences in COM kinematics between obese

and lean participants were found (Figure 4a,b). Based on these results, it appears that

when exposed to the same initial conditions (either initial angular displacement or

velocity) obese and lean individuals exhibit similar COM kinematics during recovery

from small postural perturbations.

Considering two biomechanical mechanisms may help understand how the obese

achieved similar COM kinematics during balance recovery. The increased moment of

inertia in the obese contributed to a reduced initial angular velocity when all participants

were exposed to identical force perturbations. Increased mass and moment of inertia,

however, elicit increased gravitational and inertial loads in the obese, requiring

increased ankle torque for recovery (Figures 3c,f and 4c). The peak ankle torques do

not appear to approach the maximum force generating capacity of the obese

participants [29], and so the increased torque demands seen here do not appear

problematic for recovery from these perturbations. However, larger perturbations may

demand larger torques exceeding the capacity of obese musculature and leading to

imbalance. In addition to increased moment of inertia, ankle stiffness can have a large

influence on the COM kinematics following a postural perturbation. In fact, much of the early correction torque following a postural perturbation is attributed to ankle stiffness [21]. Since obese participants exhibit increased ankle plantar flexor torque during quiet standing to support their increased body mass (Figure 5 and [21]), ankle stiffness would also be increased [30] prior to, during, and in response to the perturbations. As such, this ankle stiffness may have offset (at least partially) the increased mass and moment of inertia in the obese by generating a corrective torque during balance recovery.

Epidemiological evidence and biomechanical studies investigating the effects of increased body weight on postural sway [9-12] indicate an increased risk of falls in the obese. Our results show no differences or less/slower COM movement in obese participants in response to small postural perturbations, which does not imply an impaired balance recovery ability. Therefore, it appears our results may conflict, in a broad sense, with existing studies. However, since most falls occur in response to a postural perturbation [18], it seems as if the current study offers a higher level of external validity than studies involving quiet standing. It is possible that different biomechanical and/or physiological mechanisms are responsible for the effects of obesity during quiet standing and in response to small postural perturbations. For example, increased postural sway observed in previous studies in the obese during quiet standing could be explained in part by a possible decreased plantar sensitivity due to increased body weight [31-35]. However, this may not contribute to impaired balance recovery from small postural perturbations in the present study because the perturbations were larger than those normally experienced during quiet standing, and

thus easier to detect. It is also possible that the effect of obesity on balance recovery

increases as the magnitude of the perturbation increases. Perhaps the obese have a

decreased risk of falls from small postural perturbations because their increased inertia

has a steadying effect and the muscle forces required to recover balance are within the

capabilities of most individuals. However, larger perturbations would introduce larger

inertial forces and demand higher muscle forces. As such, the obese could have an

increased risk of falls from large postural perturbations due to limited relative strength

available for counteracting the increased inertial forces. Based upon this reasoning, our

results may not conflict with existing literature, but instead provide a better

understanding of balance and falls in the obese.

Studies have reported increased COP velocity in the obese during quiet standing [10,

11], yet this was not observed in the present study. Two differences between the

present study and these earlier studies may contribute to the inconsistencies in findings.

First, differences in the mean subject age between the studies were different. The

previous studies included adults with an average age of 40 [10, 11] while the current

study included adults with an average age of 22. The effects of obesity on balance may

be influenced by age such that the effects of obesity are more apparent as age

increases. Second, the obese participants included in the present study had BMI

values ranging from 30.1-36.9 kg/m^2 while the two previous studies included those with

BMIs as high as 63.8 kg/m^2 [10] and 50.5 kg/m^2 [11]. In fact, the results from [10]

showed that the effects of obesity increase as body weight increases. Comparing our

results to their correlation, using our lean participants' average weight of 69.6 kg, they

reported a COP velocity of 0.65 cm/s while we found it to be 1.2 cm/s. At our obese

participants' average weight of 106.5 kg, they reported a COP velocity of 0.85 cm/s

while we found it to be 1.4 cm/s. While the values are not quite of the same magnitude,

a similar increase in COP velocity between the lean and obese was observed in both

studies (ours and [10]).

Several limitations of this study warrant discussion. First, as with all cross-sectional

experimental designs, additional differences between the lean and obese groups other

than BMI could have contributed to our results. However, we could not identify any

such factors. Second, the perturbations were presented in order of increasing difficulty

instead of being randomized, so it is possible a learning effect could have occurred.

However, these learning effects would only have affected our results if lean and obese

participants learned at different rates, and we are aware of no evidence to support a

difference in learning rate. Third, to our knowledge no relation between our dependent

variables and a risk of falls has been established. Therefore, we can only infer a link

between COM kinematics after a postural perturbation and risk of falls. Fourth, it is

unclear at this point if our results can be generalized to obese individuals with BMI

values larger than those tested here, and with different ages. Other studies of obesity

and balance have included older and younger individuals than those tested here with

BMIs extending well above the normal obesity range.

In summary, obese participants exhibited no differences in movement or less/slower

movement than the lean participants when using an ankle strategy to recover from small

forward postural perturbations as well as during quiet standing. These results imply that

obesity in young adult males did not impair balance recovery for the tasks investigated. The apparent inconsistency between our results and those from other studies that indicate an increased risk of falls in the obese may be explained by different biomechanical and/or physiological mechanisms between the different tasks. Additional research is needed to improve our understanding of factors influencing the risk of imbalance and falls in the obese.

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Chapter 3 - Summary and Future Directions

Summary

Obesity is a major and growing concern associated with numerous health conditions. It is also related to many musculoskeletal impairments, altered posture and gait, and diminished standing balance performance, all of which are linked with an increased fall risk. The majority of falls are thought to result from some kind of postural perturbation, yet the biomechanical mechanisms as to why obese individuals fall more often than lean individuals is unclear. Therefore, the goal of this study was to investigate the effects of obesity on balance recovery in response to small forward postural perturbations. Participants were exposed to two types of postural perturbations, and they attempted to recover balance with only an ankle strategy. The first type of postural perturbation was applied with a pendulum to deliver force impulses to the participants such that they had an initial angular velocity. The second type involved releasing participants from a static forward lean such they had an initial angular displacement from normal standing posture. Quiet standing trials were also conducted for a comparison with the literature. Obese individuals exhibited less center of mass (COM) displacement and a slower COM velocity compared to lean individuals when exposed to identical force perturbations. When exposed to identical force perturbations relative to body weight, and when released from identical lean angles, no differences in COM kinematics were found. During quiet standing, no differences in mean center of pressure (COP) velocity were observed between obese and lean groups. In all tasks, the obese generated higher ankle torque than the lean.

The obese participants exhibited no differences in movement or less/slower movement than the lean participants when recovering from small forward postural perturbations as well as during quiet standing. These results imply that obesity in young adult males did not impair balance recovery for the tasks investigated. While previous studies indicate a possible increased risk of falling in the obese, our quiet standing and perturbation results do not. This may be explained by different biomechanical and physiological mechanisms such that our results may not conflict with existing literature, but instead provide a better understanding of balance and falls in the obese.

Future Directions

Additional research is needed to improve our understanding of factors influencing the risk of falls in the obese. Quiet standing balance and balance recovery should be explored for an extended range of ages and BMIs within the same task. This ensures that the results for that task do not apply only to a portion of the obese population. In addition, more challenging tasks (e.g. larger perturbations) could be administered such that a step would be required for balance recovery. This could help to identify a threshold difference between lean and obese balance and the biomechanical mechanisms that influence increased falls in the obese.

This work will be submitted to Gait and Posture in November of 2008.