Invited Review

Biomechanical Effects of Obesity on Balance

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ABSTRACT

International Journal of Exercise Science 5(4) : 301-320, 2012. The objective of this review was to analyze the current literature related to the effects of obesity on balance. These effects were observed during conditions of static balance, perturbed balance and dynamic balance during gait. The literature review included studies focused on the biomechanical effects of obesity, the relationship between weight loss and balance, and the relative efficacy of weight loss as a balance intervention. The older adult population, which faces increased risk of falls and related injuries, was highlighted where targeted research was available. The existing literature provides evidence for a strong link between obesity and balance impairments. This meta-analysis supports the efficacy of weight loss as an intervention to improve balance in the obese. Additional investigations are needed to confirm the reliability of relationships noted in this review paper, and to explore the potential of weight loss in simple and combined interventions. Future research should also determine whether efficacy differs among populations.

KEY WORDS: Postural control, balance, obesity, biomechanics, gait

INTRODUCTION

Obesity is a major global health issue. Self-reported obesity prevalence in the United States is over a third of the adult population, despite the promotion of a U.S. Surgeon General health objective to reduce the rate to 15% by 2010 (17). Worldwide, the incidence of obesity has more than doubled in the past 30 years (104). This sustained growth in the prevalence of obesity suggests that current interventions are ineffective; it is reasonable to expect greater numbers of individuals to experience the conditions associated with excess body weight.

Significantly increased body weight is considered to be a factor in heart disease, diabetes, stroke and some types of cancer (77, 99). Individuals with a body mass index (BMI) of over 35 may face an increase in mortality of 40% in females and 62% in males, as compared to individuals with BMI in the normal range (72). The obesity epidemic is a potential threat to the decades-long decline in American mortality rates (77). Globally, overweight and obesity comprise the fifth leading risk factor for mortality, resulting in some 2.8 million annual deaths (104).

In addition to an overall increase in mortality, obese individuals face a greater risk of mobility impairments (48, 61). Obesity is a risk factor for functional decline in both genders, and the risk increases with body mass (57, 35). Individuals with higher waist circumference and body mass demonstrate difficulty in bending, kneeling, stooping, lifting and carrying (42, 56). Problems with executing these basic physical tasks creates limitations in maintaining strength and mobility, as well as in performing basic activities of daily living (42, 56).

More research is needed to fully define the structural and functional limitations imposed by overweight and obesity, but available studies suggest that increased body weight does interfere with normal musculoskeletal function through a variety of kinetic and kinematic impairments. These physical adaptations lead to impaired balance, abnormal gait patterns and increased incidence of muscle weakness – the top 3 risk factors for falls in older adults (5, 41, 105).

The objective of this article is to review the current literature related to the effects of obesity on balance, including those studies which focus on weight loss as an intervention for improving or reversing balance impairment in the obese. The article first presents an overview of the biomechanics of postural stability, and then examines the relationship between deviated biomechanics and fall risk. The next section focuses on evidence that obesity may contribute to impairments that increase falls and associated injuries. Finally, the article presents literature on the relationship between weight loss and adaptations in the biomechanics that affect balance. Since loss of balance is a greater concern to older adults, this population is highlighted where information is available in the literature (96, 18). Additional supporting literature on the general adult population is also included.

POSTURAL STABILITY AND FALLS

Falls: Frequency and Consequences

Approximately a third of community-dwellers aged 65 and over experience a fall each year, with that proportion rising to 50% for those over the age of 80 (96). Falls are the leading cause of death from unintentional injuries in adults over 65 years old, comprising 47.9% of all deaths due to unintentional injuries (18). Approximately 10% of older adults will experience a serious injury as the result of a fall. These may include fracture, head injury and joint dislocation (87). In addition to the immediate necessity of medical treatment, moderate to severe injuries may increase the risk of early death (94). Older adults who do not recover from a fall may face loss of independence and institutionalization (11, 63). Impairment of functional ability is also a significant predictor of mortality in the elderly (45).

Background on Postural Stability

Postural control is any act of maintaining, achieving or restoring balance in any static or dynamic posture. Balance is the state of equilibrium whereby the net force, or sum of forces, acting on the body is zero (81). In practice, this means that in order to maintain balance, postural control strategies must be employed to counteract forces that act to move the body out of equilibrium.

A frequently used model of these postural control strategies is the inverted pendulum model. The model assumes that the body is rigid and rotates solely about the ankle joint, hence the imagery of an upside-down pendulum with the body swaying about the ankle (34). This model also reflects the “ankle strategy” of postural stability, with the muscles about the ankle joint as the primary movers. These muscles control posture by generating corrective torque in proportion to the disturbance that displaces the body’s center of mass (COM) (74). This disturbance can be the result of an external force such as a push, or an internal force such as a voluntary movement. Though the inverted pendulum model is a simplification of the mechanisms by which humans achieve balance, as all joints are involved in maintaining posture. COM displacements of body segments and lower limb joint angles significantly correlate with the displacement of whole body COM. This suggests that the inverted pendulum model is a valid prediction tool for postural control (34, 102).

In addition to coordinating movement to balance internal and external forces, the human body must also adhere to a range of postures within which it is possible to maintain balance. This range of postures includes daily activities such as lifting and stooping. These postures require that the COM be within the body’s base of support (BOS). When the line of gravity – the path of the COM towards the ground – falls outside of the BOS, the body’s balance is compromised [81]. Since both internal and external forces are acting on the body at all times, the muscles of the body must respond to these forces to maintain balance. This leads to a force-compensation pattern that causes small spontaneous sway in body movement when maintaining a posture [64]. Spontaneous sway is seen in all upright positions. The tiny angular deviations from equilibrium are accelerated by gravity-induced torque and then countered by corrective muscle torque stabilizing the body. Body sway is often measured for research by using movements in center-of-pressure (COP), typically of the foot, to approximate displacement of the body (71).

Predicting Risk of Falls and Associated Injuries

Maintaining balance involves a complex interaction of multiple intrinsic and extrinsic factors. In fact, more than 400 individual risk factors contribute to the incidence of falls in older adults (21). In surveys of both independent-living and community-dwelling seniors, motor control and balance are the top two underlying factors in the occurrence of falls (5, 105). Compromised balance is also the top contributor to falls as estimated by heath care providers (105). A review of factors cited in related research literature shows the primary contributing factors to falls include: balance deficits, gait impairments and muscle weakness (5, 41, 105).

Mobility and balance deficits may be reflected in impaired ability to stand, transfer motion, lean or reach, and respond to perturbation (21). The efficacy of these motions is measured through variations in COP or body sway in static balance tests. Since the goal of postural control is to minimize fluctuations in body sway by correcting them quickly, the size and speed of these shifts provides an indication of the efficacy of postural control mechanisms within the body (78).

Gait abnormalities also reflect balance impairments. Gait may be compromised through reduced velocity, cadence, step width, and step length, as well as through increased stance duration (21, 37, 79). Older adults who are less able to control or adapt these gait attributes to the environment may have difficulty avoiding obstacles which contribute to falls (79). Reduced gait speed among older adults is significantly related to balance measures and the incidence of falls (85).

Older adults who experience falls are more likely to demonstrate reduced leg strength that may inhibit the ability to maintain postural balance (37, 3, 25, 49). Muscle strength may be especially important in the ability of older adults to prevent a fall by recovering balance after perturbation. During balance recovery, it is essential to harness lower body muscle strength, both by producing a high rate of torque generation for motion correction and by coordinating movements at the knee and ankle joints (4, 46). Muscle fatigue also contributes to the reduction of muscle strength, and has the potential to reduce both force production and balance control by increasing postural sway and altering attributes of gait (46, 58).

The three contributing factors discussed above also influence the frequency of injury in individuals who experience falls. Slower gait speed, difficulty in performing a tandem walk and poor performance in the sit-to-stand test are predictive of hip fractures in older adults who do experience falls (23, 24). One leg balance is also a significant independent predictor of injurious falls (97). Although reduced bone density is certainly a risk factor for fracture, women who experience hip fracture have only slightly lower bone density of the femoral-neck than women who do not experience fractures in falls. Therefore, other factors must make significant contributions to fracture risk during falls. The relationship between postural stability assessments and risk of bodily damage may be related to the ability of the individual to coordinate a corrective muscular response during a fall (24).

THE IMPACT OF OBESITY ON POSTURAL STABILITY

Biomechanics of Obesity

Obesity significantly changes the way the body moves by causing changes in anthropometry (see table 1). Increased body weight and mass modify how the limbs and whole body create and react to forces (83). Excess adiposity also interferes with the interaction of joints and muscles that are crucial to functional capacity and postural balance (9).

Chambers et al. (19) examined the effects of obesity on body segment anthropometry in the obese geriatric population and observed that body mass distribution varied with both obesity and gender. Normal weight males had greater trunk and upper extremity segment mass as compared to women. However, obese elderly individuals showed a significantly greater trunk segment mass, regardless of gender. This is representative of the increased abdominal fat that is correlated to higher BMI (53, 55, 82).

The propensity toward increased abdominal fatness contributes to the anterior shift of the body’s COM (22, 6, 62).

This modification is particularly consequential as an anterior displacement of the COM significantly increases the magnitude of ankle torque required to stabilize the body in the upright stance. An anterior shift in whole body COM also threatens stability by placing the line of gravity closer to the boundary of the body's BOS (22).

Range of motion (ROM) is also an important facet of functional movement (table 1). Capacity of joint ROM in the trunk and lower limbs may influence the ability to maintain and recover balance, especially as the amplitude of perturbation increases (103). This is especially relevant in the obese, for whom recovery from perturbations of large amplitude may present the most significant balance challenge (70).

Gilleard and Smith (38) observed a decreased capacity to forward flexion of the thoracolumbar spine in obese adults, both while sitting and standing. The authors posited that ROM was limited due to decreased forward stability. Increased fatty tissue in the abdominal area may also create a physical barrier to full ROM during some movements. Impairment in angular displacement of the thoracic segment and ROM in the thoracolumbar spine was exacerbated as weight increased. Bertocco et al. (7) observed the same limitation in trunk flexion when obese adults performed the sit-to-stand task.

Postural deviations are also common in obese individuals. As a result of limited ROM and modified distribution of mass, the obese adopt chronic postural adaptations that threaten functional capacity by leading to back pain and spinal shrinkage during physical tasks (84). Fabris de Souza et al. (30) determined that 100% of morbidly obese subjects showed abnormal postural deviations. These included angular deviations in any direction between the body axis and joints. The most prominent deviations in the obese occurred in the spine, knees and feet.

An example of a postural modification is seen in the strategy employed by the obese in order to rise to standing. Obese individuals show higher knee joint torque compared to hip joint torque (maximal 0.75 $Nm \cdot kg^{-1}$; 0.59 $Nm \cdot kg^{-1}$) while this is reversed in normal weight persons (maximal 0.38 $Nm \cdot kg^{-1}$; 0.98 $Nm \cdot kg^{-1}$) (7, 88). Normal weight subjects maximize forward trunk flexion in order to avoid high torque at the knee joint. Obese individuals may avoid this strategy both in order to prevent vertebral column torque (which may exacerbate back pain) and as a result of limited capacity to flex the trunk.

Normal weight subjects maintain a consistent strategy in the sit-to-stand test despite the presence of fatigue over time. Obese subjects, on the other hand, adopt the strategy of their normal weight counterparts as fatigue increased over the trials. Employing a strategy of increased trunk flexion is likely necessary in order to complete later trials, suggesting that the strategy of increased knee torque has situational limitations that might affect real-world physical activities (7, 36).

Obesity and Gait

As a result of biomechanical adaptations to obesity, many gait variables are impaired in the obese population. These include reductions in speed, cadence, and stride, as well as an increase in support base. Modifications in gait result in functional impairments, poor muscle coordination and force production, and reduced resistance to fatigue (30). Gait abnormalities have been used precisely to predict mobility deficits in adults and were found to be more prevalent in adults with greater waist circumference (1). Gait adaptations may result from the necessity to improve postural stability and to reduce the effect of ground reaction forces (GRF) that contribute to osteoarthritis and pain (see table 1).

Evidence shows that the joint articulating surfaces in the lower limbs do not scale significantly with body size (27), suggesting that an increase in absolute GRFs is relevant. Browning and Kram (14) found that peak vertical GRF were 60% greater for obese subjects as compared to their normal weight counterparts. The amplitude of the GRF was greater than would be predicted according to body mass; obese subjects had a mass 61% greater than normal weight subjects but experienced 91% greater medial peak of the mediolateral (ML) GRF. Messier et al. (73) similarly found that joint loading decreases significantly with weight loss. For each step taken, joint load at the knee is reduced 4-fold for each one-pound reduction in body weight.

Browning and Kram (14) discovered that stride width was increased by about 30% in obese subjects, across all speeds of walking. This adaptation increases lateral stability and is a likely contributing factor to the disproportionate increase in GRF observed in the obese (28, 29). Browning and Kram (14) also noted an increased peak external knee adduction moment in obese subjects that may be an adaptation to redistribute GRF across the knee. Slower walking speeds decrease both GRFs and the absolute net muscle moments (N-m) required to maintain the pace of walking (14, 26).

Joint rotation also differs in obese subjects at the hip, ankle and knee, even at a self-selected walking speed. Hip abduction angles vary significantly at various points in the walking cycle, while ankle dorsiflexion is significantly greater and ankle plantar flexion is significantly smaller in obese individuals as compared to their normal weight counterparts. The authors suggest that these may be an adaptation to the physical obstacle to normal movement created by excess adipose tissue (92). As with postural deviation in the obese, researchers discovered an anterior tilt of the trunk in obese individuals during walking which may interfere with normal gait patterns (20).

Despite the potential to reduce GRFs and the associated metabolic expenditure, obese subjects appear to prefer walking speeds that are very similar to those observed in the normal-weight population (12, 13). Some researchers suggest that gait attributes are less modified in the obese than would be expected due to the capacity of these individuals to compensate for the increased metabolic costs and GRF by making kinematic adaptations. These adaptations could explain why the metabolic cost of walking is just 10-12% higher in obese individuals, despite much higher predictions based on the increased step width and hip circumduction (lateral leg swing) seen in obese walkers (13,15).

Obesity and Strength

As previously discussed, an increase in body mass requires additional force production for movement, including those motions necessary to maintain and correct body posture. Corbeil et al. (22) modeled the human body using a 15-segment mathematical humanoid to determine the relationship between obesity and postural control. This model showed that abdominal obesity would theoretically limit the range of stability boundaries in the obese by creating an anterior displacement of the COM. This anthropometric shift results in a significantly greater ankle torque requirement for stabilization during perturbations. If this force cannot be produced, the obese person is more susceptible to loss of stability and falls.

Research studies have typically recorded a higher level of absolute strength in both the trunk and lower limb muscles of obese individuals as compared to their normal weight peers. However, when corrected for the independent effect of fat free mass or adjusted for total body weight, obese individuals actually have lower levels of strength and power output than lean counterparts (54, 60, 67). This may be especially significant in women, who show a minimal rise in fat free mass as body mass increases (60, 59, 86).

Postural stability in the obese may also be limited due to motor delays precipitated by increased inertia of the limbs, as well as ROM and muscular strength limitations (9). Combined with a limited ability to generate force, obese individuals may lack the capacity to coordinate the rapid multi-joint movements required to regain postural control when perturbed (9, 22, 100). These delays are particularly significant as Corbeil et al. (22) calculated that torque required for stabilization increases non-linearly when motor response is delayed at onset or in time to peak torque.

Obesity may also compromise the ability to resist muscular fatigue. Muscular fatigue impairs balance control and requires a greater level of cognitive resources for balance coordination (89). Park et al. (80) discovered that excessive fat mass significantly increased the rate of perceived exertion of postural stresses. Maffiuletti et al. (67) determined that resistance to muscle fatigue in the quadriceps is reduced in obese individuals, potentially interfering with the ability to maintain and correct postural balance. What is currently not well understood is whether reduced resistance to fatigue is the cause or the effect of compensatory changes in gait in obese individuals. An understanding of these underlying neural mechanisms would provide important information for intervention and rehabilitation strategies.

Obesity and Balance

Overweight, central obesity and overall level of muscular fitness are strongly associated with balance deficiencies in the elderly. BMI is a major performance determinant in a wide range of both static and dynamic balance field tests (45, 68, 91). Obesity also increases the need for attentional resources to maintain postural stability. This may lead to compromised balance when subjects are required to maintain stability during distraction such as while multi-tasking during daily life activities (75).

Table 1. A comparative summary illustrating the interrelationships of the effects of obesity on posture, balance, gait, and strength and their impact on activities of daily living (ADLs).

		Posture	Balance	Gait	Strength	Impact on ADLs
Increased Overall Body Weight		Greater A-P and M-L shifts during stance [39]	Increased COP displacement and speed due to decreased sensitivity of plantar mechanoreceptors [8, 31, 40, 51, 47]	Increased GRFs resulting in gait abnormalities [1, 14, 73]	Greater absolute strength but lower relative strength and power [54, 60, 67]	Susceptibility to increased falls and instability
Increased Segment Mass	Increased trunk segment mass [19]	Limited thoracolumbar flexion results in chronic poor posture [38]	Anterior shift in COM towards limits of BOS leading to postural instability [22]	Increased stride width to increase lateral stability but increases GRF at knee joint [28, 29]	Increased knee joint torque required in sit to stand to overcome lack of trunk flexion [7, 88]	Altered strategy for sit-to-stand due to back pain and spinal shrinkage [84]
	Increased inertia		Motor delays may cause reduced ability to react to perturbation [22] Possible increase in resistance to perturbation [70, 76]	Slower walking speeds due to metabolic cost and/or kinematic modifications [13, 15]	Increased muscle force required to move segments [45, 90] Increased ankle torque required to correct postural sway [22]	Reduced functional mobility with increased step width and decreased gait speed Increased fatigue requiring greater cognitive involvement affecting dual tasks [89, 80, 75]
Excess Adiposity	Decreased range of motion	Angular deviations of joints from normal body axis [30], alters line of gravity and joint moments in stance	Decreased ability to recover from perturbations [103, 70]	Differences in joint rotation at the hip, knee and ankle throughout gait cycle [92]	Increased knee joint torque required in sit to stand to compensate for loss of ROM in trunk flexion [7, 88]	Decreased functional capacity due to increased fatigue over repetition of tasks [7, 36] Modification of movements due to physical obstacle of increased tissue [92]

Body fatness is inversely associated with walking and balance abilities, suggesting that body composition is a greater concern in the obese and morbidly obese (45, 90). The reason for this may be that an increase in mass requires a proportional increase in muscle force to maintain control during postural instability. This could also explain why women's postural stability is more easily impacted by overweight than the abilities in men. Although the presence of even moderate overweight (BMI > 29) has a significant effect on women's performance in balance tests, men's performance is not compromised unless subjects experience obesity (BMI > 30). This may be due to a greater relative level of muscle strength on average in men (45, 68).

Although most studies on obesity and balance in the elderly naturally focus on the potential for causation of falls, research in the general adult population provides a broader picture of the relationship between body weight and balance capacity. Greve et al. (39) discovered a positive correlation between postural instability and BMI. This study observed greater shifts in both lateral and anteroposterior directions by obese subjects in order to maintain stability. Adapted response to perturbation was seen at an increase of 20% in body mass.

Using mean speed of foot COP to approximate balance stability, Hue et al. (51) estimated the contribution of body weight to postural stability in conditions of vision and no vision. With eyes open, body weight accounted for 52% of variance in balance stability. With eyes closed, the contribution of body weight was 54% of variance. The study noted a strong correlation between increased body weight and decreased postural stability, as evidenced by increased COP speed to maintain stability, decreased mean peak stability times and increased mean distance between stable positions.

These measurements suggest that obese persons are less responsive to perturbation than normal weight subjects. One potential explanation for this decreased sensitivity is the increase in mean pressure that the mechanoreceptors – the body's sensory receptors for pressure – are under due to an elevation in body weight. Several studies observed an increase in plantar contact areas and pressure levels in the heel, mid-foot and metatarsal areas (8, 31, 40, 47). It is possible that this constant and elevated pressure interferes with the function of the mechanoreceptors that is necessary to inform the body's response to oscillation.

Whatever the mechanism, it seems likely that obese individuals are challenged in recovering balance once a postural perturbation occurs. Although Miller (76) measured minimal differences in COM kinematics during perturbation between obese and non-obese subjects, the study may have been limited in the amplitude of perturbation applied to the subjects (70). Berrigan et al. (6) observed increases in both COP speed and displacement. The study focused on dynamic balance and found that obese subjects also shifted COM anteriorly during goal-oriented reaching which may compromise balance by shifting weight towards the edge of the body's BOS.

In addition to the potential variance in postural response due to differences in the amplitude of perturbation, the type of perturbation may also play a role in response variation among obese and normal weight subjects. Matrangola and Madigan (70) determined that balance recovery was compromised when obese individuals experienced perturbations that involved an initial angular velocity. When the loss of balance involved only an initial angular displacement, no difference was observed. Perturbations with little or no angular velocity may have less effect on obese individuals as their body weight increases inertia of the limbs, potentially improving stabilization.

One study saw an improvement in static postural stability with increased weight for subjects with moderate obesity. Mediolateral postural sway decreased in all patients with high BMI. The range of forward voluntary center of foot pressure - a measure of dynamic stability - was inhibited only in those patients with a BMI above 40. These findings may suggest that obese individuals have more stable postural balance, but may still experience more difficulty in compensating for loss of balance (9). While researchers with contrary findings dispute the study's methods (10, 44), other investigations support the potential for obesity to increase resistance to perturbation (70, 76).

Obesity and Falls

The mathematical model of Corbeil et al. (22) showed that obesity could theoretically disrupt postural equilibrium, increasing the risk of falls. This theory is supported by a variety of experimental and observational studies of older adults. Finkelstein et al. (32) examined a cross-section of the non-institutionalized US population over the course of three years. The researchers revealed that overweight individuals faced an increased risk of injury – 15% more likely for overweight individuals and up to 48% more likely for individuals in the Class III obesity category (BMI > 40). Overweight and obese individuals were at significantly greater risk of experiencing a fall, as well as sprains, dislocations and fractures as a result of falls and other accidents.

In a study by Fjeldstad et al. (33), 25% of obese subjects reported a history of falls compared to only 15% of normal weight subjects. Obese subjects were approximately twice as likely to have experienced a history of ambulatory stumbling, but little difference was seen between obese and normal weight subjects in static balance. The study also found that a history of falls correlated to lower Health-Related Quality of Life (HRQL) scores which suggests that increased incidence of falls in the overweight has farther reaching effects than the potential for fall-related injuries.

One potential complication of studying cause-effect relationships in falls is the possible effect that the actual fall experience has on physiological factors. Falls and related injuries affect kinematic characteristics as well as influencing the ability to maintain and coordinate muscle tissue (25, 33). Although compensatory adaptations in gait might be expected in subjects with a history of falls, these individuals show greater variability in kinematics than older adults who experience a fall (2). This suggests that although some balance and kinematic measures may be reflective of the results of a fall rather than contributing factors, these tests may still reliably discriminate predictive attributes of those at risk for future falls.

THE EFFECTS OF WEIGHT LOSS

Limited literature exists on the effect of weight loss on balance and the propensity to fall that comes with obesity. However, the available results unanimously suggest that a reversal is possible (table 2). One concern with the potential for balance improvement via weight loss is the

Table 2. Summary of research articles on effects of weight loss on biomechanical parameters of posture and gait.

Article	Participants	Weight Loss Method	Biomechanical methods	Biomechanical parameters	Results	Mean (±) 95% CI of selected variables
Teasdale et al. 2007	Control (n = 16) BMI < 25kg Obese (n = 14) BMI < 39.9 Morbid Obese (n = 14) >40 kg	Obese: hypocaloric diet 15-47 weeks (until weight stable) Excess obese: bioliopancreatic surgery	Kistler force platform (200 Hz) Quiet stance eyes open/eyes closed (14 trials of 35 sec)	Mean COP displacement speed, and RMS in A/P and M/L directions	Significant weight loss in both obese groups Obese groups significantly reduced COP speed COP speed decreased with increasing weight loss	COP speed *difference* (pre to post) eyes open (cm/s) Control: 0.00 (± 0.1) Obese: 0.11 (± 0.2) Excess obese: 0.18 (± 0.2), after 12 months 0.30 (± 0.3)
Handrigan et al. 2010	Control (n = 15) BMI < 25kg Obese (n = 10) BMI < 39.9 Excess Obese (n = 10) >40 kg	Obese: hypocaloric diet 15-47 weeks (until weight stable) Excess obese: bariatric surgery	Kistler force platform (200 Hz) Quiet stance eyes open/eyes closed (7 trials each) for 35 sec.	Mean COP displacement speed, and range values in A/P and M/L directions	Significant weight loss in both obese groups Obese groups significantly reduced COP speed	COP speed *difference* (pre to post) eyes open (cm/s) Control: 0.002 (± 0.03) Obese: 0.10 (± 0.04) Excess obese: 0.18 (± 0.10), after 12 months 0.28 (± 0.2)
Hortobagyi et al. 2011	Control (n = 10) BMI 21.8 ± 2.8 Obese (n=10) BMI 43.2 ± 6.5	Roux-en-Y gastric metabolic surgery	AMTI force platform (960 Hz), Qualisys motion capture (120 Hz) 10 walking trials at self selected and standard speed (1.5 m/s)	Kinetic: GRF; joint torques Kinematic: swing time; stride length; gait velocity; joint ROM	Significant weight loss in obese group Significant reductions in GRF and increases in joint torques Significant increases in swing time; stride length; velocity; joint ROM	GRF (N): Pre 1320 ± 309; Post 924 ± 264 Swing time (%): Pre 35.3 ± 1.9; Post 37.8 ± 2.0 Stride length (m): Pre 1.38 ± 0.11; Post 1.49 ± 0.18 Hip ROM (deg): Pre 30.2 ± 4.13; Post 34.1 ± 7.2

A/P: Anterior-Poster direction, M/L: Medial-Lateral direction, COP: Center of Pressure, RMS: Root Mean Square frequency of muscle loss during body weight reduction (93, 98).

As discussed, limb strength is an integral component of postural balance. This interdependency suggests that resistance training should be part of balance recovery interventions in overweight older adults in order to minimize loss of lean body mass. However, weight loss alone still effects significant improvements in postural balance even with concomitant loss of absolute strength (43, 52).

Weight loss modifies the kinematic and kinetic attributes that compromise balance capacity in overweight and obese individuals. Hortobágyi et al. (50) had preliminary findings consistent with re-adaptations including: increased stride length, higher gait speed, reduced vertical GRFs, lower frontal plane adduction torques and normalized ankle plantarflexion torques (see table 2). The study looked at subjects prior to and six months following bariatric surgery. These results suggest that kinematic adaptations to obesity are not permanent and can be restored to normal values through weight loss.

In a similar study, Teasdale et al. (95) followed morbidly obese men through bariatric surgery, and observed a group of obese men through weight loss via caloric restriction (see table 2). Nearly all postural stability measures were improved with weight loss, including foot COP speed and range in both the AP and ML axes, both with and without vision. The study detected a strong linear relationship between weight reduction and improvements in balance control.

Handrigan et al. (43) examined obese patients who underwent bariatric surgery as a weight loss intervention, compared to obese individuals who engaged in diet modifications (see table 2). In both groups, weight loss correlated to a reduction in absolute knee muscular strength. The loss of strength was approximately 10% on average in obese subjects and 33% in extremely obese subjects. Despite the loss of strength, balance control, as indicated by average foot COP speed, improved approximately 12% for obese and 27% for the extremely obese group after weight loss.

Only the extremely obese group showed an increase in relative strength (22%) after weight loss, indicating that increased relative strength is not the primary mechanism for balance improvement after weight loss. This study investigated static balance which research suggests is improved with increased mass (9, 70, 76). These results are very supportive of weight loss as a balance intervention, especially in the extremely obese.

Exercise Versus Weight Loss for Recovery of Balance

Although a wide range of studies have focused on the potential for physical activity to reduce the risk factors of falls and to improve balance recovery in older adults, there is no consensus on the ideal exercise intervention for fall prevention. This is largely due to the complicated interaction of multiple risk factors in falls, and to the very wide range of potential exercise programs that can be employed as interventions (16).

Conversely, there appears to be limited research directed towards comparing the relative effects of weight loss and exercise on the recovery of balance in overweight individuals. Matrangola and Madigan (69) conducted a small study of nine obese male subjects. They examined dynamic recovery of balance using an ankle strategy, which is the situation in which obese individuals are most vulnerable to falls (9, 22, 33, 101). Both human subjects and dynamic computer simulations were used to create a model of balance recovery capacity.

Matrangola and Madigan (69) determined that both strength training and weight loss were effective in improving the ability of obese individuals to recover balance during perturbation. However, the amount of weight loss required to effect change was smaller than the necessary increase in strength level. The study calculated that for maximum lean angle to improve by one degree, a strength increase of 15.3 ± 1.1% was required, while an 8.6 ± 0.8% decrease in weight effected the same change. The disparity in effect became more pronounced as greater improvements in balance were targeted.

The balance improvement effected in the Matrangola and Madigan [69] study may represent an important functional change for subjects. Using very similar methods, Mackey and Robinovitch (65) found that the average maximum dynamic recovery angle varied between young and elderly subjects by about 36.1% - a difference of 2.6° ($P < 0.001$). Although the proposed improvement in maximum lean angle appears quite small, the change may substantially affect performance in older adults.

Matrangola and Madigan's (69) findings do not clarify the practical significance of implementing weight loss versus strength training interventions in the elderly. Although the weight loss required to effect significant change is quantitatively smaller than the required strength gain, it is difficult to determine which improvement is more practical in the older adult population. This could vary widely with the individual's physiological and environmental limitations. Mobility limitations are more common in elderly individuals due to age or previous fall injury. This could particularly limit their potential to improve balance capacity through exercise training, making improvement through weight loss a welcome alternative.

There is also evidence that although weight loss alone does improve balance, the recovery is amplified in a combined intervention. Maffiuletti et al. (66) conducted a brief 3-week weight loss program on 19 obese and 20 extremely obese subjects. The program also included balance training for a subset of subjects. Weight loss between the two groups was comparable – 4.9% reduction in BMI for the non-training group and 5.3% BMI reduction for the group that received balance training. There was no difference observed in postural stability between the groups at baseline. After the body weight reduction program, time of balance maintenance and postural sway were significantly improved ($p < 0.05$) for subjects who engaged in a combination of weight loss and balance training, but not for those who were treated with weight loss alone.

CONCLUSION

By its very nature, obesity has a pronounced effect on the anthropometry of humans. Mass and corresponding inertia are increased in all body segments, changing obese individuals' movements and responses to force. Although some adaptations compensate for anthropometric changes, shifts in the body's total COM are difficult to adjust for without compromising normal patterns of movement.

These changes, along with reductions in ROM that result from elevated body weight, often lead to postural deviations. Similar adaptations are seen in gait patterns, in order to adapt the obese body to increased GRFs and the increased metabolic cost of movement. The anterior shift of the body's COM not only threatens postural stability by moving the body towards the limits of its BOS, the change also increases the muscle torque required to stabilize even small deviations in the body's postural position.

Unfortunately, the additional force necessary to maintain postural control may not be available to obese individuals. Obesity reduces relative muscular strength and decreases muscular fatigue resistance. These two limitations may lead to motor delays and insufficient corrective torque, both potential contributors to an inability to effect an appropriate response to perturbation which allows for the maintenance of postural control.
Impairment in balance capacity raises the risk of falls for obese individuals. Furthermore, the incidence of falls increases with body mass, suggesting that it might be possible to decrease risk with any weight loss rather than a return to normal weight. Obese individuals also experience an elevated risk of fracturing bones. People with high body mass break more bones overall during falls, despite experiencing some level of protection for central bones such as the femur.

The literature supports the potential for weight loss to improve or restore some of these physical adaptations to obesity. With high levels of weight loss, patients demonstrate significant increases in relative strength and significantly improved measures of postural stability. The limited available research also suggests that although weight loss alone may positively influence postural balance, weight loss in conjunction with strength and balance training may be the most effective intervention to improve balance capacity in the overweight and obese, in order to reduce the risk of falls and fracture.

This is clearly a new area of focus for biomechanical research. The few investigations that have been completed point to important correlations between body weight and balance capacity. However, these studies must be connected by additional research to determine the specific changes that can be expected with varying levels of weight loss, and how these changes will affect particular kinematic and kinetic body attributes. Direct comparisons among interventions must be made in order to clarify their relative contributions to balance performance. Additionally, future research should further subdivide the population of overweight individuals by age, gender and lifestyle factors to better inform efforts to reduce the rate of injury due to falls.

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