THE UNIVERSITY OF HULL

THE EFFECTS OF WEIGHT LOSS ON THE BIOMECHANICS OF WALKING GAIT IN HEALTHY OVERWEIGHT AND OBESE ADULTS: A SYSTEMATIC REVIEW

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Abstract

Obesity is an increasing problem in the developed world with a negative impact on health and quality of life. Weight loss interventions (both lifestyle and surgical therapies) are used as a treatment for clinical obesity and comorbidities. Obesity has been shown to adversely affect the activities of normal daily living, including walking gait and musculoskeletal function. However due to the excess fat mass of obese individuals it is difficult to measure biomechanical effects on gait. The aim of this systematic review was to determine **the effects of different weight loss interventions (dietary energy restriction, physical activity/exercise and surgery interventions) on the biomechanics of gait in healthy overweight and clinically obese adults.**

Six electronic databases were searched for relevant journal articles. Published studies were screened for eligibility according to the predetermined inclusion and exclusion criteria. Seventeen relevant publications were selected for inclusion in the systematic review. Twelve studies used surgery as a weight loss intervention; with two of these including additional exercise after surgery. Five studies used diet and/or exercise as the weight loss intervention; with one using exercise only, one using dietary restriction only, three using combined dietary and exercise/physical activity interventions. The intervention durations ranged from 3-weeks to 48-months, with the surgery interventions typically having longer follow-up.

Nine studies compared the participants' baseline measurements to their post intervention measurements. Four studies were randomised controlled trials comparing the weight loss

intervention to a control group. Two studies were non-randomised controlled trials, where the experimental group were undergoing surgery and were compared to a control group.

Eleven studies measured gait through functional walking tests which were used to measure gait (walking) velocity. Four studies incorporated more detailed gait analysis outcome measures; including temporal-spatial parameters, with three of these studies also reporting kinematic and kinetic outcome measures.

Participants in all studies lost body mass after the dietary restriction, exercise and surgery interventions. Baseline mean body mass index (BMI) ranged from 30.6 ± 3.8 to 51.1 ± 9.2 kg/m^2 with significant body mass reductions evident in all studies (post intervention BMI ranged from 28.2 ± 8.1 to 40.4 kg/m^2). Gait velocity improved after weight loss from the separate dietary restriction, exercise training and surgery interventions.

Nine studies measured gait through functional walking tests. The improvement in gait velocity ranged from 0.02 – 0.43 m/s. Overall, more improvement was evident within two surgical intervention (0.05 – 0.15 m/s) studies compared to two studies evaluating diet and exercise intervention (0.05 – 0.08 m/s) with direct gait velocity measures. There has been limited research on gait kinematics and kinetics after weight loss. As a result, there was limited overlap in measurement outcomes in the two studies undertaking 3D gait analysis following weight loss surgery which made it difficult to compare the results of the outcome measures.

Further research is required on how weight loss affects the walking gait of obese individuals, especially after dietary and exercise interventions. From the published research, weight loss interventions have significant benefits for the improvement of gait temporal-spatial parameters and to reduce the risk of developing further musculoskeletal disorders. The limited 3D gait analysis available suggests that there is an improvement in gait function following weight loss.

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1. Introduction

Obesity is a widely recognised problem in the UK and globally that is expected to continue to increase in the future (Craig, Mindell, & Hirani, 2009). Due to the present way of life the risk of obesity is increased through the modern (convenience and fast food) diet and from lack of exercise due to transportation and sedentary lifestyles (Department of Health, 2011b). Obesity has been evidenced across the lifespan affecting all ages from children to the elderly (Ko, Stenholm, & Ferrucci, 2010; Sallinen et al., 2011; Samson et al., 2001; Shultz, Anner, & Hills, 2009; Shultz, Browning, Schutz, Maffeis, & Hills, 2011; Vincent, Raiser, & Vincent, 2012). As an individual progressively gains body mass and develops obesity there are detrimental effects on health, functional mobility and quality of life (De Zwaan et al., 2009; Kushner & Foster, 2000; Mazzocchi et al., 2012; Wee, Davis, Huskey, Jones, & Hamel, 2013).

Obese individuals with related health problems may find it difficult to undertake activities of daily living (Backholer, Wong, Freak-Poli, Walls, & Peeters, 2012; Evers Larsson, 2004; Naugle, Higgins, & Manini, 2011; Tsuritani et al., 2002). An important activity of daily living is walking as it allows independence and mobility. Increased adiposity limits mobility and has a detrimental effect on internal musculoskeletal structures. Increased biomechanical strain is placed on joints when walking due to the excess mass (Sheehan & Gormley, 2012; Wearing, Hennig, Byrne, Steele, & Hills, 2006b). Obese individuals may have lower muscular strength for their body mass as they have excess fat mass (Duvigneaud et al., 2008; Maffiuletti et al., 2007).

Health education and lifestyle modification may help to reduce obesity in future generations by making the current lifestyle more active and dietary habits healthier (Gabriel et al., 2011). The main treatment for obesity is dietary energy restriction (henceforth termed dietary intervention) and increased physical activity/structured exercise training for weight loss to improve health and quality of life. Obese individuals commonly find it difficult and/or uncomfortable to undertake activities of daily living such as walking and stair climbing. This in turn makes it harder to encourage them to participate in physical activity (Kushner & Foster, 2000; Mazzocchi, et al., 2012; Wee, et al., 2013). Bariatric surgery is another option but is currently only used for severe obesity or clinical obesity with metabolic complications (Asher, Burrows, & Collins, 2013; Silver, Torquati, Jensen, & Richards, 2006).

Following weight loss interventions, obese individuals have been shown to exhibit improvements in physical functioning (Josbeno, Jakicic, Hergenroeder, & Eid, 2010; Vincent, et al., 2012; Wedin, et al., 2012), including mobility (Errickson et al., 2011), general health (Maffiuletti et al., 2005) and quality of life (Evers Larsson & Mattsson, 2003; Pronk & Wing, 1994; Silver, et al., 2006). However there is limited research evaluating the gait of obese individuals after weight loss treatments and how it relates to healthy normal weight individuals (Hortobagyi, Herring, Pories, Rider, & De Vita, 2011).

Previous research on the effects of weight loss on the biomechanical parameters of the gait pattern in obese populations has been unclear. Previous investigations of weight loss interventions have utilised different weight loss interventions and limited outcome measurements with little consistency across studies. The aim of this systematic review is to determine:

The effects of different weight loss interventions on the biomechanics of gait in healthy overweight and clinically obese adults.

The knowledge gained from this systematic review will consolidate all published studies reporting the effects of weight loss interventions on gait in obese individuals and identify areas for further research.

2. Literature Review

In this chapter, obesity will be put into the context with respect to: the classification and characteristics of the obese population; types of interventions used for weight loss; the effect of obesity on the biomechanical parameters of gait and quality of life; the problems and limitations encountered with obesity research.

2.1 Classification of Obesity

2.1.1 Body Mass Index

In recent years the average mass of British individuals has increased (male: 78.9 kg in 1993 to 83.6 kg in 2008, female: 66.6 kg in 1993 to 70.2 kg in 2008) (Craig, et al., 2009). Obesity is often classified using a body mass index (BMI). A normal BMI is between 18.5 and 25 kg/m^2, overweight or pre-obese is between 25 and 30 kg/m^2, and obese is over 30 kg/m^2. The obese classification can be further split into three categories, class I is from 30 kg/m^2 to 35 kg/m^2, class II is from 35 kg/m^2 to 40 kg/m^2, class III or morbidly obese is over 40 kg/m^2 (WHO, 2006). Between 1993 and 2008 obesity in the UK has increased from 13% to 24% for the male population and from 16% to 25% for the female population (Craig, et al., 2009). Although BMI is a simple and easy way to classify obesity there are also flaws as BMI does not take into account percentage body fat and muscle mass. An athletic individual can be classed as obese on BMI due to muscle tissue being heavier than fat tissue (Handrigan et al., 2012).

2.1.2 Body Shape

Alternate ways to classify obesity are by measuring waist circumference and waist to hip ratio. Generally fat mass is distributed around the abdomen and thorax in males (android) and around the pelvis and thighs in females (gynoid) (Menegoni et al., 2009; Sarkar, Singh, Bansal, & Kapoor, 2011). Increasing waist circumference has been linked to increasing health risks for overweight individuals (male: low < 94 cm, high 94 – 102 cm, very high > 102 cm, female: low < 80 cm, high 80 – 88 cm, very high > 88 cm) (Craig, et al., 2009). Waist circumference measurements collectively measure intra-abdominal and subcutaneous fat (Haight, Lerner, Board, & Browning, 2014). Circumference measurements are an easy and simple way to classify obesity as long as measurements are taken consistently; it is also an easy indicator to show weight loss as circumferences decrease with reduced body fat. By combining the hip and waist circumference measurements the waist to hip ratio can be calculated. This gives a ratio which takes into account muscle mass through the hip circumference measurements as well as intra-abdominal fat from waist circumference (Dalton et al., 2003; Welborn, Dhaliwal, & Bennett, 2003). Waist to hip ratio has the best correlation for predicting cardiovascular disease in obese adults compared with waist circumference alone and BMI (Dalton, et al., 2003; Welborn, et al., 2003).

2.1.3 Measuring Body Fat

Waist circumference and BMI measurements do not take into account the difference between fat mass and fat free mass. An individual is considered to be obese if the percentage body fat is ≥ 25% in men and ≥ 35% in women (Peltz, Aguirre, Sanderson, & Fadden, 2010). There are several methods that can be used to measure body fat. A common way to measure body fat is with skinfold callipers. However, there are assumptions made on the average thickness of subcutaneous adipose tissue for the whole body which may not be consistent on obese individuals (Creaby, Hunt, Hinman, & Bennell, 2013). There may also be variation between measurements taken by different clinicians (Creaby, et al., 2013). Using a using duel energy X-ray absorptiometry (DEXA) or magnetic resonance imaging

(MRI) scanner is the most accurate way to classify obesity through body fat percentages, however these are costly methods and not suitable for all individuals (Ritz, Sallé, Audran, & Rohmer, 2007; Thomson, Brinkworth, Buckley, Noakes, & Clifton, 2007; Verdich et al., 2011). Bioelectrical Impedance Analysis (BIA) is a cheaper alternative to measure body fat percentages but is not as accurate with obese individuals as DEXA scanners because the predictive equations used to calculate body composition are based on hydration of fat free mass in healthy normal weight individuals (Y.-C. Li et al., 2013; Ritz, et al., 2007; Verdich, et al., 2011).

2.1.4 Classification of Obesity Summary

The most accurate method to measure body fat in obese individuals is DEXA and MRI scanners. These are expensive and not always available to use. Skinfold callipers and hip to waist ratios can be used but may make obese individuals uncomfortable when measurements are being taken. This is the reason that BMI is still widely used and most reported method to classify obesity.

2.2 Characterisation of Obesity

2.2.1 Centre of Mass

The centre of mass (COM) of a body is the point where the mass of the body can be considered to act (Watkins, 2007). The COM of the body is balanced when it is within the limits of stability determined by the base of support (Cruz-Gómez, Plascencia, Villanueva-Padrón, & Jáuregui-Renaud, 2011). The position of the COM depends on the mass distribution of the body but is usually located in the pelvic region (Watkins, 2007). When walking, the moving body segments continuously alter the COM position (Siervo et al., 2012). In obese individuals, the body segments are altered to reduce the effect of excess fat mass on COM position (Clark, 2004). A greater mass is more difficult to stabilise due to inertia increasing the risk of falling in obese individuals (Clark, 2004; Corbeil, Simoneau, Rancourt, Tremblay, & Teasdale, 2001; Paquette, Teasdale, Prud'Homme, & Tremblay, 2000; Teasdale et al., 2007). During standing, Menegoni et al. (2009) found obese males increased medial-lateral sway due to increased mass over the hips but not in obese females as they had a lower COM from a gynoid obesity shape. In the anterior-posterior direction both males and females had increased sway with increased body mass. However Cruz-Gomez et al. (2011) found no gender effects in obese males and females on postural sway. This could be due to the foot positioning on the force plates, Cruz-Gomez et al. (2011) positioned participants according to the manufacturers reference whereas Menegoni et al. (2009) had ~8 cm between participants heels and foot angle at 30°.

The effects of mass distribution and COM position would have a greater effect during locomotion (Arellano, O'Connor, Layne, & Kurz, 2009). Sarkar et al. (2011) found that obese males had a significant increase in step width during gait but changes in obese female step width were insignificant. With obese males having a higher COM position compared to females the wider step width provides a wider base of support for maintaining balance during gait.

2.2.2 Muscle Strength

Having to support excess body mass may have a small training effect on lower limb muscles to increase muscle strength in obese individuals (Duvigneaud, et al., 2008; Hulens, Vansant, Lysens, Claessens, & Muls, 2002; Hulens et al., 2001; Maffiuletti, et al., 2007). Peak internal knee extensor moment is greater than knee flexor moment as weight bearing has a training effect on the quadriceps muscles (Hulens, et al., 2002). However, it has been shown that although obese subjects have higher absolute muscle strength, when normalised to fat free mass they have lower muscle strength (Duvigneaud, et al., 2008). This was shown by Hulens et al. (2001) where absolute obese quadriceps extension strength was 137.9 Nm compared to 123.6 Nm in lean women but relative strength was significantly lower (6 – 7% for extension, 18 – 20% for flexion). Maffiuletti et al. (2007) found a similar result with significantly lower (-32%) relative concentric and isometric quadriceps moment and power in obese compared to lean males but higher absolute moment and power (16 – 20%) with significantly greater fat free mass in obese males (18%). Excess mass carried by obese individuals is fat rather than muscle which leads to lower muscle strength (Duvigneaud, et al., 2008; Maffiuletti, et al., 2007).

2.2.3 Energy Expenditure

Any activity where energy expenditure is increased is beneficial for weight loss in obese individuals. From carrying additional mass it would be expected that the energy expenditure of obese individuals would be greater. During gait, due to heavier limbs more energy would be required for movement. Browning et al. (2009) found that external mechanical work had no effect on the metabolic cost of walking as obese and normal weight adults had similar stride length and ground reaction force (GRF) when walking on a treadmill. However, part of the metabolic cost of walking in obese adults could be attributed to increased step width (30%) as lateral swing would be more mechanically costly. Browning et al. (2007) found the metabolic cost of walking increased with leg loads and more so for added loads at more distal locations. A 16 kg increase at the waist increased metabolic rate by 32% and 4 kg added on the foot increased metabolic rate by 36% due to inertial parameters more energy would be required to move additional mass.

After weight loss, reduction in mass of the legs is expected to reduce metabolic cost when walking more than mass lost from the torso (Foster et al., 1995).

Ehlen et al. (2011) found that a slower gait velocity on an incline had a similar metabolic cost to faster level gait in obese individuals. Although net muscle moments for the hip, knee and ankle were lower on an incline; this suggests that it would be more beneficial for obese individuals to walk slowly up an incline rather than faster on level ground when exercising as the joint loads would be lower.

2.2.4 Characterisation of Obesity Summary

Reduced muscle strength and a slightly altered COM position can alter the dynamic balance of obese individuals. This may mean obese individuals have to alter their gait and use more energy to overcome these difficulties and keep control of their limb movements.

2.3 Weight Loss

In order to reduce the effects of excessive joint loads during locomotion in the obese population weight loss is recommended. Diet, exercise and surgery have been used to reduce body mass individually and in combination.

2.3.1 Dietary Intervention

After a 3-month weight loss programme of 1000 – 1200 kcal/day Plewa et al. (2007) found obese women increased walking velocity and as a result had shorter stance and double support time, longer swing time and increased cadence and stride length. As well as improving locomotion, weight loss increased physical activity levels which positively influenced muscle strength and also improve functional activities such as picking objects up from the floor, rising from a chair, stair accent and decent and carrying something heavy

(Evers Larsson & Mattsson, 2001), this was found by Evers Larsson (2004) with improvements in functional activities after 14% weight loss from dieting. Hue et al. (2008) found 10.1% decrease in absolute maximum force production (715.4 N) after weight loss of 11.8 kg (12.1%) from energy restriction (700 kcal/day for 15 – 47 weeks until body mass stabilisation) with no exercise training so absolute maximum force decrease is directly related to body mass lost. For obese individuals to lose body mass, energy restriction is initially most effective (Pronk & Wing, 1994). However, there may be reduction in muscle strength if fat free mass is lost so diet with exercise is recommended (C. T. Miller et al., 2013; Strasser & Schobersberger, 2010).

2.3.2 Exercise

After a 12-week aerobic or resistance exercise training programme, Sarsan et al. (2006) found no significant difference between training groups in body mass lost in obese women as diet was not controlled. Distance walked in the six minute walk test (6MWT), abdominal and triceps strength improved in both aerobic and resistance training groups and significant improvements in hip abductor, quadriceps, biceps and pectoral muscle strength were found in the resistance training group. This shows resistance exercise is most effective in maintaining and improving muscle strength (Strasser & Schobersberger, 2010).

2.3.3 Dietary Intervention and Exercise

Weiss et al. (2007) found reducing energy intake by 16 – 20% for one year significantly reduced absolute thigh muscle mass and knee flexor strength but no decrease was shown when normalised to body mass. However, one year of exercise six times/week preserves thigh muscle mass and strength (Weiss, et al., 2007). After 3-weeks of 1200 – 1800 kcal/day energy restriction and one hour exercise five times/week Maffiuletti et al. (2005) found obese subjects significantly improved body composition, physical performance and cardiovascular risk factors. Males lost 3 kg (4%) of fat free mass but females mainly lost fat mass. A 4-week diet and fitness programme significantly improved distance walked in the 6MWT (495.6 ± 141.1 m to 560.2 ± 132.4 m) by 64.6 m which is close to the clinically meaningful change of 70 m (Errickson, et al., 2011). After one year, obese subjects who continued to lose body mass had significantly higher muscle strength for the 1 repetition maximum leg press.

Weight loss has been shown to be more important than muscle strength when it comes to improving balance of obese individuals (Handrigan, et al., 2012; Handrigan et al., 2010). Handrigan et al. (2010) found an improvement in balance with weight loss in obese individuals but a decrease in absolute muscular strength. This is also seen with athletic obese and obese subjects with similar BMI, both groups had increased sway compared to normal weight individuals during standing but the athletic group had significantly greater absolute and relative muscle strength (Handrigan, et al., 2012). This suggests that to improve the balance of obese individuals weight loss is more effective than improving muscle strength. Improvements in balance have been directly correlated to the magnitude of weight loss in obese men (Teasdale, et al., 2007).

Unless both diet and exercise is controlled it is difficult to determine which has the greatest weight loss effect and how it affects postural stability and dynamic balance during locomotion. However, it is most likely that a combination of both diet and exercise would be most beneficial to reduce energy intake and increase energy expenditure through exercise and at the same time maintain muscle mass (C. T. Miller, et al., 2013; Votruba, Horvitz, & Schoeller, 2000; Weinheimer, Sands, & Campbell, 2010). After initial weight loss, exercise is most effective for weight maintenance (Donnelly et al., 2004; Pronk & Wing, 1994; Votruba, et al., 2000)

2.3.4 Bariatric Surgery

Bariatric surgery is used for morbidly obese individuals for fast and extreme weight loss. To be considered for surgery obese individuals generally have to have a BMI > 40 kg/m^2 or BMI > 35 kg/m^2 with at least two comorbidities (Asher, et al., 2013; Silver, et al., 2006). Bariatric surgery also has immediate beneficial effects on reducing type 2 diabetes and other metabolic factors (NICE, 2014). King et al. (2012) found four out of five bariatric surgery candidates reported limited abilities to walk more than a mile due to physical discomfort suggesting that after bariatric surgery morbidly obese individuals would be enabled to become more mobile. After bariatric surgery, obese individuals improve the distance they can walk during the 6MWT (Maniscalco et al., 2006; Tompkins, Bosch, Chenowith, Tiede, & Swain, 2008). Before surgery subjects walked 55% of the distance healthy subjects walked, six months after surgery an improvement of 33% (137 m) occurred with a reduction of 34% in BMI (Tompkins, et al., 2008). Maniscalco et al. (2006) found a similar improvement in distance walked by obese individuals after surgery (nearly 150 m). The improvement in distance walked correlate to reduction in BMI as lower BMI individuals had faster walking velocity (Maniscalco, et al., 2006). The improvements in distance walked may also be due to reduced energy expenditure required for overcoming friction between thighs and between arms and trunk when swinging arms and legs as they would have a reduced girth (Tompkins, et al., 2008). However, Castello et al. (2011) only found an improvement in distance walked during 6MWT when obese subjects participated in aerobic exercise for four months after bariatric surgery suggesting that an exercise programme is required after surgery to improve functional capacity.

2.3.5 Bariatric Surgery and Exercise

Stegen et al. (2011) also showed that exercise after bariatric surgery was important. They found muscle strength decreased (-16% quadriceps, -36% biceps and -39% triceps) four months after gastric bypass surgery with no exercise training but an improvement of muscle strength (+72% quadriceps, +27% hamstrings and +12% biceps) was found with aerobic and resistance exercise after surgery. Improvements in quadriceps strength helped to improve sit-to-stand and distance walked in 6MWT in the training group. Although there was a difference in muscle strength between the untrained and exercise groups, both lost muscle mass (7.6 kg in untrained vs. 5.4 kg in training group). A loss of muscle mass was seen through a reduction in absolute muscle thickness of quadriceps femoris muscle and cross sectional area after surgery (Lyytinen, Liikavainio, Paakkonen, Gylling, & Araokoski, 2013). In comparison Hue et al. (2008) found a decrease in absolute maximum force production of 33.5% in lower limbs (493.9 N) and 14.4% in upper limbs after 46.3% weight loss from surgery, but showed an increase of relative muscle force for both upper (57.8%) and lower (27.8%) limbs. Even with the loss in absolute muscle force there was increased balance control in the morbidly obese subjects suggesting a more stable posture and better control of upper limb movements (Hue, et al., 2008). To counteract the effect of muscle mass loss after bariatric surgery exercise should be used to improve muscle strength as obese individuals have lower relative strength (Stegen, et al., 2011).

2.3.6 Weight Loss Summary

Bariatric surgery is usually a last resort option for morbidly obese individuals but in order for it to be effective there must be a lifestyle change. After surgery healthier eating and increased physical activity should be incorporated for weight maintenance and for obese individuals to benefit their daily functional activities and quality of life.

2.4 Effects of Obesity on Gait

For obese individuals to be mobile they need to be able to walk comfortably without feeling pain. To minimise the effects of carrying additional fat mass and reduced relative muscle strength obese individuals adapt their gait pattern. There are slight alterations to kinematics and kinetics to accommodate carrying excess fat mass and pain when walking (Da Silva-Hamu et al., 2013; DeVita & Hortobagyi, 2003; Freedman Silvernail, Milner, Thompson, Zhang, & Zhao, 2013; Lai, Leung, Li, & Zhang, 2008; Sheehan & Gormley, 2013).

Browning & Kram (2007) suggested a critical level of BMI > 40 kg/m^2 before alterations in gait kinematics would occur, this would also depend on muscle strength and how long an individual has been obese. Vismara et al. (2007) suggested that the pathological gait patterns occurred in obese adults over 30 years old due to the progressive effect of excessive joint loads over the years.

2.4.1 Temporal-Spatial Parameters

As obese individuals alter their gait to accommodate excess body mass it will affect their temporal-spatial parameters. Changes to the gait parameters include walking with a shorter step length, a wider base of support, reduced swing duration and longer double support duration which makes obese individuals walk at a slower velocity than lean individuals (Błaszczyk et al., 2011; De Souza et al., 2005; Malatesta et al., 2009; Sheehan & Gormley, 2013; Spyropoulos, Pisciotta, Pavlou, Cairns, & Simon, 1991; Vismara, et al., 2007).

2.4.1.1 Six Minute Walk Test (6MWT) – Distance Walked and Walking Velocity

There is a negative correlation between BMI and distance walked in 6MWT (Beriault et al., 2009; Dourado & McBurnie, 2012; Gontijo et al., 2011; Iwama et al., 2009). Evers Larsson & Reynisdottir (2008) found that BMI explained 38% of variance in distance walked for

6MWT, where obese participants with BMI > 41 kg/m^2 walked 84 m less than obese participants with a lower BMI; overall obese participants walked 77% of the distance of lean participants (obese group mean = 534 m, range 285 – 716 m). Similar distances were walked when Gontijo et al. (2011) compared healthy weight and obese males and females (healthy weight males 604.68 ± 46.47 m, obese males 547.81 ± 68.16 m, healthy weight females 583.44 ± 43.75 m, obese females 522.61 ± 48.54 m). These results agreed with the American Thoracic Society where the two main factors for reduced 6MWT distance were excess body mass and being female (Gontijo, et al., 2011).

When walking velocity was calculated from the 6MWT, lean women walked at a faster velocity (7.2 km/h) than obese (5.9 km/h) and morbidly obese women (4.4 km/h) (Hulens, Vansant, Claessens, Lysens, & Muls, 2003). Obese females also walked at a significantly slower velocity and covered less distance on a treadmill 6MWT than healthy weight females (obese 6.2 ± 0.7 km/h, 582.1 ± 71.3 m vs. healthy weight 6.7 ± 0.7 km/h, 633.3 ± 61.0 m) (Di Thommazo-Luporini et al., 2012). Distance walked improved in obese individuals after 12-weeks of resistance or aerobic training (Sarsan, et al., 2006) or bariatric surgery (Castello, et al., 2011; De Souza et al., 2009; Josbeno, Jakicic, Hergenroeder, & Eid, 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, Picolli, Dani, Padoin, & Mottin, 2013) which suggests an improvement in gait and physical function.

2.4.1.2 Effects of Slower Walking Velocity

In obese individuals the preferred walking velocity has been reported as between 1.06 and 1.29 m/s (Błaszczyk, et al., 2011; Da Silva-Hamu, et al., 2013; DeVita & Hortobagyi, 2003; Lai, et al., 2008; Malatesta, et al., 2009; Plewa, et al., 2007; Spyropoulos, et al., 1991; Vismara, et al., 2007) which is slower than the 1.33 – 1.64 m/s reported for healthy adults (Freedman Silvernail, et al., 2013; Kirtley, 2006; Malatesta, et al., 2009; Spyropoulos, et al., 1991).

A slower walking velocity reduces step length, and decreases cadence as fewer steps can be taken in a minute (Da Silva-Hamu, et al., 2013; Kirtley, 2006). Spyropoulos et al. (1991) showed obese men walked more slowly (1.09 vs. 1.64 m/s) than normal weight men and with significantly shorter stride length (1.25 vs. 1.67 m). De Souza et al. (2005) and Malatesta et al. (2009) found obese individuals walked more slowly with reduced cadence and step length compared to non-obese adults. However, Vismara et al. (2007) found no significant difference in the 1.9% reduction in cadence between obese and healthy subject even though the normalised gait velocity was reduced by 6.4%. This could be due to participants being younger (29.4 ± 7.9 years) than in the studies by De Souza et al. (2005) (47.2 ± 12.9 years). Also, the Vismara et al. (2007) study focussed on participants with "Prader-Willi" syndrome, a complex genetic disorder where obesity is common due to an insatiable appetite, compared to obese and healthy participants. Blaszczyk et al. (2011) found no significant difference in stride length and stride duration between obese and lean females due to no significant difference in walking velocity (control 1.08 m/s vs. morbidly obese 1.03 m/s).

2.4.1.3 Stance and Swing Duration

A greater mass is more difficult to stabilise due to inertia when standing (Paquette, et al., 2000; Teasdale, et al., 2007) but becomes even more difficult during locomotion especially during the single support phase of gait which makes obese individuals more likely to fall (Arellano, et al., 2009; Corbeil, et al., 2001; Sarkar, et al., 2011; Wu, Lockhart, & Yeoh, 2012). Studies have shown that obese individuals all reduced the swing phase duration, amount of time in single support and increased stance phase duration and amount of time in double support as a mechanism to improve stability during gait (Błaszczyk, et al., 2011; Browning & Kram, 2007; Lai, et al., 2008; Malatesta, et al., 2009; Plewa, et al., 2007; Sheehan & Gormley, 2013; Spyropoulos, et al., 1991; Vismara, et al., 2007). The longer stance duration is used to generate adequate push off force to overcome inertia (Spyropoulos, et al., 1991).

2.4.1.4 Base of Support and Stance Width

Excess fat mass alters the COM movement during gait which may make obese individuals more unstable during locomotion (Wu, et al., 2012). As well as reducing the time spent in single support during gait another mechanism used to improve the stability of obese individuals during gait is to increase the stance width and foot angle, which gives obese individuals a wider base of support during gait (De Souza, et al., 2005; Spyropoulos, et al., 1991; Vismara, et al., 2007; Wu, et al., 2012). Measured stance width for normal weight participants is between 8 – 10 cm but can increase to 10 – 16 cm for obese participants (De Souza, et al., 2005; Spyropoulos, et al., 1991). Vismara et al. (2007) found obese participants had increased external foot rotation compared to healthy participants (13.7 ± 5.2° vs. 6.88 ± 3.96°) and Sarkar et al. (2011) found as gait velocity decreased the degree of toe out increased.

Malatesta et al. (2009) found obese participants had 47% greater lateral COM displacement during gait. Browning & Kram (2007) found an increase of 91% for medial-lateral GRF with an increase of 61% body mass in obese participants compared to non-obese participants, the increase in medial-lateral GRF had a significantly positive correlation with increased step width in the obese participants (0.15 m vs. 0.10m for normal participants). Increased medial-lateral GRF and lateral COM displacement could make obese individuals more susceptible to falling during locomotion (Clark, 2004; Corbeil, et al., 2001; Paquette, et al., 2000; Teasdale, et al., 2007). A positive correlation between transverse coefficient of friction and significantly greater step width in the obese males compared to non-obese males (160.09 mm vs. 115.01 mm) could potentially cause lateral slipping during weight acceptance (Wu, et al., 2012).

Use of increased stance width during gait may also be used to reduce the friction between the legs due to excess adipose tissue and increased thigh girth of obese individuals (Browning, et al., 2009; Malatesta, et al., 2009; Spyropoulos, et al., 1991; Vismara, et al., 2007; Westlake, Milner, Zhang, & Fitzhugh, 2013; Wu, et al., 2012). After bariatric surgery thigh circumference reduced significantly due to less subcutaneous fat (Lyytinen, et al., 2013). Westlake et al. (2013) showed increasing thigh circumference on healthy weight adults increased step width compared to just adding mass to the thighs.

2.4.2 Kinematics

As well as altering temporal-spatial parameters, obese individuals have reduced joint range of motion (ROM) (Ling, Brotherton, & Smith, 2009; Lyytinen, et al., 2013; Park, Ramachandran, Weisman, & Jung, 2010). This is due to excess mass around joints which affect the amount of movement.

2.4.2.1 Range of Motion

Obese individuals may alter their gait pattern due to having a reduced capacity for ROM and muscle weakness (Naugle, et al., 2011). Excess fat mass around the joints may reduce the ROM that the joint can move through. This was shown by Park et al. (2010) where obese males with a BMI > 40 kg/m^2 had significantly reduced ROM for shoulder joint extension and abduction, lumbar spine extension and lateral flexion and knee joint flexion. However this study used morbidly obese males so may not be accurate for individuals with lower BMI or females. The reduced ROM is dependent on fat distribution around the body especially at the abdomen which would inhibit flexion at the waist and ROM at the hip (Blake, Miller, & Brown, 2000; Ling, et al., 2009). ROM may also be affected by reduced physical activity of obese individuals which could decrease flexibility at some joints (Evers Larsson & Mattsson, 2001). After surgery, Lyytinen et al. (2013) showed improvements in knee flexion ROM and internal and external hip rotation from reduced fat mass surrounding joints. Despite obese individuals having reduced ROM, some studies have found that ROM during gait were similar to gait kinematics of healthy weight individuals due to not using the full joint ROM (Browning & Kram, 2007; Freedman Silvernail, et al., 2013; Lai, et al., 2008; Vismara, et al., 2007).

2.4.2.2 Angular Displacement – Sagittal Plane

Ankle

Reduced plantar flexion after initial contact (IC) for weight acceptance is related to reduced stride length (Spyropoulos, et al., 1991). Increased plantar flexion at toe off (TO) may be due to obese individuals requiring extra propulsive forces to advance a heavier limb into swing phase (Cimolin et al., 2011; DeVita & Hortobagyi, 2003). However, Spyropulos et al. (1991) found obese men had reduced plantar flexion at TO which reduced push off force and reduced swing time and stance length. Reduced peak plantar flexion at TO is also seen with increased load (10, 20, 30 kg) (Han & Wang, 2011). Sheehan and Gormley (2013) found no differences in ankle angles. This may be due to Sheehan and Gormley

(2013) using overweight participants (BMI > 25 kg/m^2) rather than obese participants (BMI > 30 kg/m^2) (Cimolin, et al., 2011; DeVita & Hortobagyi, 2003).

Knee

DeVita & Hortobagyi (2003) found that obese participants had reduced knee flexion during loading response compared to healthy weight participants which da Silva-Hamu et al. (2013) attributed to the slower gait velocity of obese women. Reduced knee ROM and peak flexion were also seen with increasing load through weighted vests (Han & Wang, 2011; B. Smith, Roan, & Lee, 2010). A hyper extended knee in stance phase may be due to excessive load and reduced muscle activity in obese individuals (Vismara, et al., 2007). Increased knee flexion during swing phase has been associated with inactivity of the rectus femoris muscle (Sheehan & Gormley, 2013) and having to move a leg mass with greater inertia, the knee flexor muscles increase action to hold the knee joint in flexion to contain the exaggerated limb forward movement during terminal swing phase (Da Silva-Hamu, et al., 2013).

Hip

Sheehan & Gormley (2013) associated an increase in hip flexion at IC with hip extensor weakness in obese subjects. Spyropulous et al. (1991) suggested that a reduced hip flexion at IC and during swing phase was due to obese men having reduced swing duration during gait and muscular effort for flexion may compromise balance due to excess mass. A reduced hip flexion in mid stance can be attributed to obese subjects having a shorter step length (Cimolin, et al., 2011). Increased peak hip flexion and reduced peak hip extension was also seen for increased load (10, 20, 30 kg) (Han & Wang, 2011). However, DeVita and Hortobagyi (2003) found obese individuals had more hip extension throughout stance phase as they walked with a more erect posture.

2.4.2.3 Angular Displacement – Frontal Plane

Ankle

Lai et al. (2008) found higher ankle eversion in midstance, terminal stance and pre swing for obese participants, however Sheehan and Gormley (2013) found no differences. As the walking velocities were similar (1.1 m/s vs. 1.12 m/s), this may be due to Sheehan and Gormley (2013) using overweight participants (BMI > 25 kg/m^2) rather than the obese participants (BMI > 30 kg/m^2) used by Lai et al. (2008) . As the obese participants would be more likely to have a collapsed medial arch which leads to increased eversion (Perry, 1992).

Knee

The maximum knee adduction angles were higher for obese participants in both stance and swing phases (Lai, et al., 2008; Sheehan & Gormley, 2013), this is contrary to findings by Freedman Silvernail et al. (2013) who found the peak knee adduction angles were significantly lower in obese subjects. With increased thigh circumference Westlake et al. (2013) found that peak knee adduction angles increased more than for just adding mass or combined mass and circumference increase. This suggests that initially an increase in thigh girth increases knee adduction angle, but with prolonged exposure to obesity knee adduction angle is reduced to prevent additional loading at the knee joint which could be related to osteoarthritis.

Hip

Obese individuals have greater hip adduction in terminal stance and pre-swing as obese participants used the adductor muscle to control lateral body sway and maintain upright stance (Lai, et al., 2008; Sheehan & Gormley, 2013; Spyropoulos, et al., 1991). Increased external hip rotation at IC widens the base of support (Spyropoulos, et al., 1991). Increased pelvis movement may be due to obese individuals having a wider stance to accommodate an increased thigh girth (Cimolin, et al., 2011)

2.4.2.4 Angular Displacement – Transverse Plane

Studies that measured angles in the transverse plane found no differences between obese participants and healthy weight participants for the ankle, knee, hip and pelvis joints (Lai, et al., 2008; Sheehan & Gormley, 2013). The only difference found in the transverse plane was increased foot progression angles for obese individuals compared to healthy weight individuals (13.7° ± 5.2° vs. 6.88° ± 3.96°) (Vismara, et al., 2007) and reduced toe angle after surgery (0.5-2.1° reduction) (Vincent et al., 2012). Increased toe out angles are used by obese individuals to widen base of support for increased stability.

2.4.2.5 Kinematic Summary

Increased girth at joints may only have a limited effect in reducing ROM during gait as angular displacement during gait does not cover the full ROM at each joint. With increased mass, joint angles are adjusted to keep centre of gravity of the whole system in the stable area for walking. Excess mass around the thighs increases stance width to reduce the friction between the thighs. Obese individuals walk at a slower velocity than normal weight individuals with longer double support time, shorter single support time and shorter stride length to improve stability during gait.

2.4.3 Kinetics

Additional mass leads to increased GRF (Birtane & Tuna, 2004; Fabris et al., 2006). Increased forces may impact on the moments acting about the joints which can cause musculoskeletal problems such as osteoarthritis, plantar fasciitis, chronic heel pain, and fibromyalgia in obese individuals (Anandacoomarasamy, Caterson, Sambrook, Fransen, & March, 2008; Sheehan & Gormley, 2012; Wearing, et al., 2006b).

2.4.3.1 Ground Reaction Forces (GRF)

As Newton's second law of motion states the resultant force is equal to the mass of a body mass multiplied by acceleration (due to gravity) it would be expected that obese individuals have increased GRF. It has been found that obese individuals have increased absolute peak vertical, anterior-posterior (AP) and medial-lateral (ML) GRF compared to normal weight individuals (Figure 1) which increased at faster walking velocities (Browning & Kram, 2007). When normalised to body mass obese individuals had lower peak vertical GRF and at slower walking velocities the 1st vertical peak was smaller but there was less effect on the 2nd vertical peak (Figure 1a) (Browning & Kram, 2007). However, Lai et al. (2008) found that the 2nd vertical peak GRF was lower in obese individuals especially with a slower walking velocity. The latter part of the GRF is used for forward propulsion (Figure 1b) and lower force generation is required during TO at slower walking velocities. After weight loss surgery there is a reduction in the absolute GRF (1st vertical peak reduced 27.6% and 1st AP peak reduced 23.8% with 27.2% weight loss (Hortobagyi, et al., 2011) 1st vertical peak reduced 20.8% and 1st AP peak reduced 19.5% with 21.5% weight loss (Bragge et al., 2014)). However Hortobagyi et al. (2011) found the normalised peak vertical and AP GRF increased after surgery due to the increase in preferred walking velocity (PWS).

Browning and Kram (2007) found the 91% increase in ML GRF (Figure 1c) was not proportional to increased mass and attributed it to increased step width. When normalised to body mass, the 1st ML peak was smaller with slower walking velocities but there was less effect on the 2nd ML peak, as the ML GRF 2nd peak acts to redirect weight onto contralateral leg and stance width is similar for all walking velocities in obese individuals (Browning & Kram, 2007). After surgery the decrease in ML GRF was significantly greater than mean weight loss due to a reduction in step width (Bragge, et al., 2014).

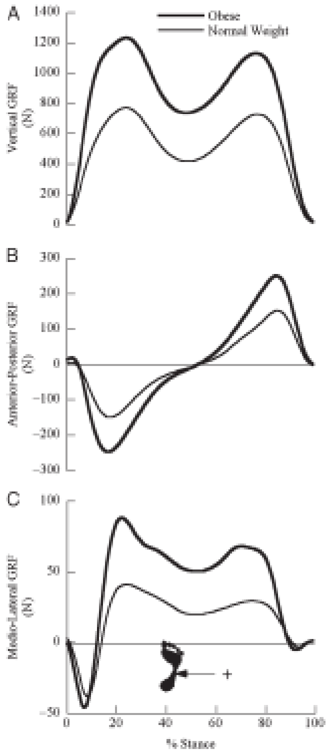

Figure 1: Mean vertical (A), anterior-posterior (B) and medial-lateral (C) ground reaction force when walking at 1.5 m/s for obese vs normal weight participants from Browning and Kram (2007).

2.4.3.2 Moments

Alterations in kinematics and differences in forces from excess body mass would be expected to alter gait kinetics in the obese population. Along with increased internal forces and no differences in surface area of articular joints and cartilage thickness, increased loading especially in the medial compartment of the knee and at the hip joint has been linked to musculoskeletal pathologies such as osteoarthritis in obese individuals (Browning & Kram, 2007; Segal, Yack, & Khole, 2009; Sheehan & Gormley, 2013). Han & Wang (2011) showed ankle, knee and hip joint moments increased on a healthy population simulating obesity with increasing loads (0, 10, 20, 30 kg at 1.28 m/s) and increasing velocity (0.8, 1.3, 1.7 m/s), this may be a reason obese individuals walk at a slower velocity to reduce joint moment.

Ankle

Obese individuals had reduced internal ankle plantar flexion moment in pre-swing along with increased peak ankle inversion moment at loading response (Lai, et al., 2008). Reduced peak plantar flexion moments during late stance phase could have an effect on reducing propulsive forces at TO which reduces gait velocity (Sheehan & Gormley, 2012). At faster walking velocities obese individuals increase plantar flexion moments at TO to increase propulsive forces (Browning & Kram, 2007; DeVita & Hortobagyi, 2003). Obese individuals may require increased ankle moments to maintain balance especially during loading response where due to increased body mass there is increased demand on muscles (Da Silva-Hamu, et al., 2013).

Knee

DeVita & Hortobagyi (2003) found that obese subjects had reduced knee internal extensor moment when walking at their preferred velocity but similar to lean subjects when walking at a standard velocity (1.5 m/s) but peak knee extensor moments were reduced by 46% when normalised to body mass. This is contrary to Browning & Kram (2007) who found obese individuals has significantly greater absolute peak knee extensor moments when walking velocities increased compared to normal weight individuals but no significant differences when knee moments were normalised to body mass. Differences in knee joint moments were due to obese participants in DeVita & Hortobagyi (2003) study having different knee kinematics whereas the obese participants in Browning & Kram (2007) had similar knee kinematics to the normal weight participants this could be due to obese participants in DeVita & Hortobagyi (2003) study having higher BMI (range 32.4 – 58.7 kg/m^2 vs. 30 – 43 kg/m^2) than the obese participants in Browning & Kram (2007) study.

Lai et al. (2008) and Sheehan & Gormley (2013) also found no differences for knee moments normalised to body mass and height.

Females had an increased knee extensor moment because of combined additional thigh mass and circumference than for only additional mass and control conditions. Males had increased knee extension moment for increased thigh circumference than for adding mass and combined mass and circumference conditions. However the peak internal abduction moment was similar for all conditions (Westlake, et al., 2013). This suggests that most alterations were made in the sagittal plane when thigh circumference and mass were increased as the moment of inertia was altered.

In the frontal plane, Segal et al. (2009) found a significantly lower second peak external knee adduction moment (KAM) in obese subjects, however Freedman Silvernail et al. (2013) saw an increase in normalised peak external KAM at increased walking velocities suggesting that obese individuals walk slower to reduce joint loading (Browning & Kram, 2007). Knee adduction angles may be related to osteoarthritis in obese individuals due to the loading in the knee joints (Freedman Silvernail, et al., 2013). As a result, obese individuals reorganise their neuromuscular function and alter the direction of the force vector relative to joint position to reduce total load at the knee joint possibly through externally rotating the leg or having a valgus knee alignment (Browning & Kram, 2007; DeVita & Hortobagyi, 2003).

Hip

Browning & Kram (2007) found obese individuals had greater absolute peak extension moments than normal weight individuals at six velocities between 0.5 – 1.75 m/s except

0.75 m/s but there was no difference when normalised to body mass. This was also seen in other studies where there was no difference between sagittal hip moments normalised to body mass for obese and normal weight individuals (DeVita & Hortobagyi, 2003; Lai, et al., 2008; Sheehan & Gormley, 2013).

In the frontal plane Sheehan & Gormley (2013) found significantly reduced hip abductor moment at IC in overweight individuals which may be linked to progression of medial knee osteoarthritis (Sheehan & Gormley, 2012).

2.4.3.3 Moments during Incline Walking

Ehlen et al. (2011) compared obese and normal weight individuals walking on a treadmill at different inclines, they found peak ankle moments during late stance phase and peak knee and hip moments during early stance phase were reduced when walking on an incline at slower velocity (0.75 m/s at 6°) than level walking at faster velocities (1.5 m/s and 1.75 m/s at 0°). Tibio-femoral joint loading was reduced in obese individuals when walking slowly uphill compared to faster level walking (Haight, et al., 2014). In the frontal plane peak internal abduction moment was reduced for slower incline walking (0.5 m/s at 9° and 0.75 m/s at 6°) compared to faster level walking (1.5 m/s at 0°) which suggests that for obese individuals it would be more beneficial to walk slower on an incline than walking faster on level ground as less force is exerted at the joints (Ehlen, et al., 2011; Haight, et al., 2014).

2.4.3.4 Angular Impulse

In obese individuals there was increased plantar flexor and knee extensor angular impulse to increase walking velocity (DeVita & Hortobagyi, 2003). At 1.5 m/s obese individuals had 89% more plantar flexion angular impulse compared to normal weight individuals

(DeVita & Hortobagyi, 2003). After weight loss surgery ankle plantar flexion and knee extensor angular impulse in early stance phase decreased significantly (Hortobagyi, et al., 2011).

2.4.3.5 Power and Work

Peak ankle absorption power (A1 power burst) during ground impact was significantly higher in obese individuals compared to normal weight individuals (Cimolin, et al., 2011). With increased velocities obese individuals produced 11% more positive work at the ankle joint and 61% more than normal weight individuals and 68% more negative work at the knee in early stance phase (DeVita & Hortobagyi, 2003). Increasing velocities and loads increased the maximum power at the ankle, knee and hip joints, the knee joint had an average negative power and the hip joint had an average positive power (Han & Wang, 2011). In healthy individuals, the average power for the ankle was close to zero for slow velocity (0.8 m/s) and low loads (0 and 10 kg) but as velocity increased (1.3 and 1.7 m/s) and for increased load (20 and 30 kg) average power became positive (Han & Wang, 2011). Increased ankle positive work occurred with faster level walking compared to slower walking on an incline but no differences for positive knee and hip joint work, whereas there was less negative work at all joints for slower walking on an incline compared to faster level walking (Ehlen, et al., 2011). In overweight individuals there was a decrease in normalised hip joint power absorption (Sheehan & Gormley, 2013) but obese individuals had greater hip power generation in early stance phase compared to normal weight individuals (Cimolin, et al., 2011).

2.4.3.6 Kinetics Summary

With increased mass the supporting force of the feet and the joint moment increases. When moments are normalised to body mass there is little difference between obese and normal weight individuals. Excess fat around lower limb joints would not help to stabilise joints during gait as lean muscle mass does.

2.4.4 Gait Kinematics and Kinetics after Surgery

After surgery improvements can be seen in walking velocity, stride length and swing time (Froehle, Laughlin, Teel, Sherwood, & Duren, 2014; Hortobagyi, et al., 2011; Vincent, Ben-David, et al., 2012). Hortobagyi et al. (2011) found a 27% initial weight loss improved gait velocity by 3.9% and after a further 6.5% weight loss improved gait velocity by a further 7.3%. Vincent et al. (2012) found a weight loss of 5% improved gait velocity by 15%. A reduction of 25% in the abdomen girth allowed for greater hip flexion and leg swing to produce longer strides (Hortobagyi, et al., 2011). However, Vartiainen et al. (2012) found no increase in stride length and reduced hip flexion at IC possibly due to a less flexed knee after 21.5% weight loss after surgery. Step width reduced after surgery (3 cm at 1.2 m/s, 4 cm at 1.5 m/s (Vartiainen, et al., 2012) and 2.5 cm at PWS (Vincent, Ben-David, et al., 2012)) suggesting reduced thigh girth and better stability. This is also seen through reduced toe angle after surgery (0.5 – 2.1° reduction) (Vincent, Ben-David, et al., 2012). Hortobagyi et al. (2011) found no changes in absolute sagittal hip and knee moment, whereas Vartiainen et al. (2012) found absolute values of moments decreased in proportion to weight loss with a reduction in absolute (internal) peak hip extensor and knee flexor joint moments but no difference when normalised. Improvements in plantar flexion moment (33.2% reduction) make gait more dynamic along with increased hip ROM and knee flexion (Hortobagyi, et al., 2011). A reduced internal knee abductor moment (24.5% reduction (Hortobagyi, et al., 2011) reduction of 18.6% in early stance and 15.6% in late stance at 1.2 m/s and 12.7% in early stance and 13.1% in late stance at 1.5 m/s (Vartiainen, et al., 2012)) could delay the onset of medial compartment osteoarthritis. The weight loss produced linear adaptations in gait at a standard velocity (1.5 m/s) and reorganisation of lower limb joint moment at self-selected walking velocity (1.30 m/s improved to 1.45 m/s) (Hortobagyi, et al., 2011). This was also suggested by Froehle et al. (2014) , where obese women improved gait parameters 4.7 years after surgery to be within 95% of age matched healthy participants.

2.4.5 Gait Summary

Prolonged and severe morbid obesity has an increased impact on joint loading. With increasing severity of obesity and age, alterations in gait during locomotion would expect to increase. The long term effects of joint loading cause obese individuals pain during daily activities. This can reduce their participation in physical activities which would increase levels of obesity and may lead to disability.

2.5 Obesity and Quality of Life

Obese individuals are more likely to have a lower quality of life through health comorbidities such as diabetes, osteoarthritis, heart disease and liver disease (Dixon, 2010; Ernersson, Nystrom, & Lindstrom, 2010; S. Li et al., 2010; Wearing, Hennig, Byrne, Steele, & Hills, 2006a). Problems with health and pain when completing activities of daily living (Backholer, et al., 2012; Evers Larsson, 2004; Naugle, et al., 2011; Tsuritani, et al., 2002) may also lead to lower mental health quality of life (De Zwaan, et al., 2009; Kushner & Foster, 2000; Mazzocchi, et al., 2012; Wee, et al., 2013).

2.5.1 Health Risks

The risk of obesity is increased through the modern diet and from lack of exercise due to modern transportation and lifestyle patterns, where energy intake is in excess of energy expenditure through physical activity (Department of Health, 2011b). Obesity can increase the risk of medical problems such as diabetes, osteoarthritis, heart disease and liver disease (Dixon, 2010; Ernersson, et al., 2010; S. Li, et al., 2010; Wearing, et al., 2006a). This has a large cost impact on hospitals and health services (more than £5bn a year in the UK) (Department of Health, 2011a, 2011b).

2.5.2 Psychosocial

Part of the psychological quality of life is body image perceptions and self-esteem which can be lower in obese individuals and reduce the likelihood of participating in physical activity (Kushner & Foster, 2000; Mazzocchi, et al., 2012; Wee, et al., 2013). Low self-esteem and perceived judgement from other can lead to anxiety and depression in obese individuals (Wedin et al., 2012). Improvements have been shown in the mental health components of the SF-36 questionnaire three months after gastric bypass surgery (Tompkins, et al., 2008). Improvements in psychosocial quality of life after weight loss may increase participation in physical activity (Vincent, Ben-David, et al., 2012).

2.5.3 Pain and Disability

Obese individuals are more likely to self-report pain (Evers Larsson, 2004; Evers Larsson & Mattsson, 2001; Peltonen, Lindroos, & Torgerson, 2003). Physical activity can also be reduced due to experiencing pain when completing activities of daily living (Backholer, et al., 2012; Evers Larsson, 2004; Naugle, et al., 2011). Most pain is reported body regions that are weight bearing such as the knee, hip, ankle and lower back (Kotowski & Davis, 2010). Pain in weight bearing regions has been shown to have improvements after weight loss (Kotowski & Davis, 2010; Peltonen, et al., 2003). As pain in weight bearing joints is prevalent in obese individuals it can be linked to musculoskeletal disorders such as osteoarthritis through high external knee adductor moments (Freedman Silvernail, et al., 2013; Peltonen, et al., 2003; Segal, et al., 2009).

2.5.4 Physical Function

Along with pain; tiredness, fear of falling and injury, discomfort and feelings of insecurity when exercising are reasons that obese individuals give for not participating in physical activity (Sallinen et al., 2009). Reduced physical activity levels can also lead to disability and functional mobility difficulties (Naugle, et al., 2011; Rolland et al., 2007). Naugle et al. (2011) showed older obese individuals with class II obesity were 18 times more likely to use compensatory strategies for functional mobility tasks than normal weight older adults such as using arm rests to push off when rising from a chair, and using the hand rail during stair ascent and stair decent tasks.

With weight loss through diet or surgery and increased levels of physical activity obese individuals can improve their health and quality of life (Evers Larsson, 2004; Josbeno, et al., 2010; Vincent, Ben-David, et al., 2012; Wedin, et al., 2012). Quality of life has been shown to improve after weight loss as functional mobility improves (Errickson, et al., 2011; Ghroubi et al., 2009; Hooper, Stellato, Hallowell, Seitz, & Moskowitz, 2007; Tompkins, et al., 2008).

2.5.5 Quality of Life Summary

Confounding health factors, musculoskeletal pain and low self-esteem lower the likelihood of obese individuals participating in physical activity. Reduced levels of physical activity can reduce psychological and social quality of life. This lowers the quality of life of obese individuals possibly leading to depression and anxiety. Weight loss leads to improvements in quality of life through increased functional mobility and self-esteem.

2.6 Measuring Gait in Overweight and Obese Adults: Limitations and Problems

2.6.1 Measuring Gait – Treadmill verses Level Walking

Treadmill gait may have differences compared to level gait due to being constrained and not show as many alterations in gait of obese individuals. While most studies on obese individuals have shown the preferred walking velocity to be slower than for healthy weight subjects there has been a range of ways gait velocity has been measured. The simplest form of gait velocity has been calculated from a level 6MWT; this is a simple, easy test to carry out on obese subjects (Beriault, et al., 2009; Maniscalco, et al., 2006) and would give an average preferred walking velocity. Using a treadmill is an easy way to control walking velocity but may have an effect on kinematics and kinetics as gait can be altered when walking on a treadmill compared to level walking. When comparing healthy subjects walking on a instrumented walkway and treadmill Wearing et al. (2013) found small significant differences in temporal-spatial parameters. The slight differences may be due to the preferred walking velocity being determined from over ground walking as preferred walking velocity on a treadmill maybe different. Temporal values were within ± 2% of gait cycle duration and spatial values were within ± 5 cm, however Wearing et al. (2013) advised that over ground and treadmill walking should not be directly compared. Riley et al. (2007) found some significant differences in peak hip and knee flexion and extension between treadmill and level walking, but lower limb moments and GRF were similar. The differences between the measured parameters were within the normal variability (Riley, et al., 2007).

2.6.2 Marker Placement for 3D Gait Analysis

Although there are many gait analysis studies on overweight and obese individuals there are more problems that have to be overcome than with healthy weight subjects during data collection. Marker placement on anatomical landmarks is difficult in obese individuals due to the excess fat mass that obscures the anatomical landmarks and may also obscure markers during movement trials (Borhani, McGregor, & Bull, 2013; Lerner, Board, & Browning, 2014; Menegoni, Vismara, Capodaglio, Benedetti, & Leardini, 2009; M. Smith, Curtis, Bencke, & Stebbins, 2013). Even after weight loss the marker placements may not be identical due to reduction in fat tissue over anatomical landmarks (Vartiainen, et al., 2012). Incorrect marker locations and soft tissue motion can induce noise in calculations (Wu, et al., 2012). The pelvis area is most problematic due to excess fat mass in the abdominal region. Smith et al. (2013) compared the traditional method of markers on the ASIS to using wand marker locations to virtually construct the ASIS location and found wand markers were within ±1° of the traditional method. However, it was only tested on overweight individuals and not obese individuals so accuracy for the obese population may not be similar. Also there can still be movement of the wand relative to the skin attachment site (M. Smith, et al., 2013). Another study by Borhani et al. (2013) compared the traditional ASIS marker placement with a cluster of three markers between the PSIS and found that the cluster method had significantly better repeatability in overweight and obese individuals. The cluster method may also have less skin movement artefact as the markers are more likely to be attached to a location with less fat mass (Borhani, et al., 2013). There were significant differences in hip flexion and anterior pelvic tilt between the basic Helen Hayes marker set and an obesity specific marker set which used a combination of additional clusters and a digitizing pointer for the pelvis landmarks (Lerner, et al., 2014).

Another way of reducing error from marker placement is to use functional joint centres where movement at the specific joint is used to calculate the joint centre rather than predicting the joint centre from assumptions relative to anatomical landmarks (Begon, Monnet, & Lacouture, 2007; Camomilla, Cereatti, Vannozzi, & Cappozzo, 2006; Corazza, Mündermann, & Andriacchi, 2007; Ehrig et al., 2011; Krauss et al., 2012; Leardini et al., 1999). Krauss et al. (2012) found statistically significant differences between the functional and predicted joint centres for all gait variables. It was suggested that functional joint centres had less sources of error as they used fewer markers and functionally determined the joint centre however as it is a newer concept it has not been validated (Krauss, et al., 2012). To accurately measure functional joint centres it may require a special motion trial especially in obese individuals who may have limited ROM particularly at the hip (Piazza, Erdemir, Okita, & Cavanagh, 2004; Piazza, Okita, & Cavanagh, 2001).

2.6.3 Inertial Parameters

Obese individuals will have different inertial parameters to healthy weight subjects so kinematic and kinetic gait calculations may not be accurate when using inertial parameters calculated by Dempster (1955) . Inertia of body segments in obese individuals also effects strength measurements as moments measured at higher velocities (240°/s) were lower in obese subjects (Hulens, et al., 2002). Folland et al. (2008) found that to make comparisons of strength and moments between populations with different body masses; strength and moments should be scaled to fat free mass as there is no influence from height whereas when moments are scaled to body mass, height has a significant influence.

Different COM for body segments and full body is dependent on how fat is distributed (Menegoni, Galli, et al., 2009; Sarkar, et al., 2011; Segal, et al., 2009). It has been shown that males have greater trunk and upper body mass (android) and females have greater lower body mass (gynoid) even for older obese adults (Chambers, Sukits, McCrory, & Cham, 2010; Menegoni, Galli, et al., 2009; Sarkar, et al., 2011; Segal, et al., 2009).

Chambers et al. (2010) found age, obesity and gender significantly altered body segment inertial parameters for COM and radius of gyration. Matrangola et al. (2008) found changes in body segment inertial parameters with weight loss due to changes in segment mass and distribution of mass along the segment longitudinal axis. Actual body segment inertial parameters can be calculated by using MRI (Matrangola, et al., 2008) or DEXA scanners (Chambers, et al., 2010) scanners.

2.6.4 Interventions

Prescribing exercise to obese individuals needs to be carefully considered as Mattsson et al. (1997) found that when walking obese women experienced higher exertion and use higher %VO_2 maximum than values for normal weight individuals. Although walking can be used as exercise for weight loss, considerations need to be made to make sure obese individuals are not over exerted. After the intervention period obese individuals are likely to regain body mass in the long term (Evers Larsson & Mattsson, 2003). In studies with follow-up after weight maintenance subjects who drop out tend to be the ones who regain body mass (Pronk & Wing, 1994). This may put off obese individuals from undertaking further weight loss interventions. However, despite a 5% regain during weight maintenance Evers Larsson & Mattsson (2003) found walking velocity was not negatively affected (baseline 71.6 ± 5.3 m/min vs. 12 weeks 75.9 ± 5.4 m/min vs. 64 weeks 75.2 ± 5.9 m/min). As well as improvements in physical functioning, psychosocial improvements in leisure time activity and well-being may make it more likely that obese individuals continue with weight loss interventions (Evers Larsson & Mattsson, 2003; Pronk & Wing, 1994; Silver, et al., 2006).

2.6.5 Limitations Summary

There is no clear standardised method for measuring gait in obese individuals due to issues with marker placement and inertial segment parameters. Besides gastric bypass surgery, there is no clear evidence on the type of diet and exercise intervention that is best for weight loss and maintenance in obese individuals. Even after a weight loss intervention it is possible for obese individuals to still be borderline obese or overweight according to the BMI classifications. For an obese individual to lose enough body mass to be classified as having a normal BMI the interventions would have to be longer than the usual 3-month duration.

With the limitations for research on obese individuals there are still questions to be answered on how weight loss affects joint loading and gait patterns during locomotion. Therefore it was necessary to undertake a systematic review to collate all information related to being overweight or obese and the effects on gait. This would be important for evaluating how these conditions affect lower limb gait parameters and identifying areas for further research that would have implications on sustaining weight loss and minimising excessive musculoskeletal loading.

2.7 Aims and Research Question

Current research on the effect weight loss has on the biomechanical parameters of the gait pattern in obese populations has been unclear. Previous investigations of weight loss interventions have utilised different weight loss interventions and limited outcome measurements with little consistency across studies. The aim of this systematic review is to determine:

The effects of different weight loss interventions (dietary energy restriction, physical activity/exercise and surgical interventions) on the biomechanics of gait in healthy overweight and clinically obese adults.

The knowledge gained from this systematic review will consolidate all published studies reporting the effects of weight loss interventions on gait in obese individuals and identify areas for further research.

3. Methodology

From the initial background literature review the specific research question was determined (Table 1). The Cochrane library was searched to see if there were any similar systematic reviews undertaken in the area of investigation to ensure the originality of the research hypothesis. The population, nature of intervention, comparative intervention and outcome measures of interest were determined and used to determine the inclusion and exclusion criteria (Table 2) (Bettany-Saltikov, 2010). From the research focus and inclusion/exclusion criteria a list of search terms for population, intervention, comparative intervention and outcome measures was created (Table 3).

Table 1: Research focus based on population, intervention, comparative intervention and outcome measures.

Population	Intervention	Comparative Intervention	Outcome Measures
obese adults	Weight loss - diet/exercise	pre vs. post	gait temporal-spatial parameters
age 18-65	surgery	comparison of overweight/obese individuals with normal weight individuals	kinematics - ankle, knee and hip angular displacement
male and female			kinetics - ankle, knee and hip moments, GRF
			weight loss
			body composition
			Health - related to quality of life

From the initial review of the literature (Table 1), the focus of the systematic review would be overweight and obese adults aged 18 – 65. This gives a broad age range, and is not halved by focussing on a specific gender. Under 18 year olds were excluded to limit the effects of children growing. Older adults were excluded to limit the effects of aging on gait, balance and functional activities (Sallinen, et al., 2011). To focus on generally healthy participants, articles on diabetes, osteoarthritis, osteoporosis, HIV and participants with mobility disorders were excluded unless the studies included a healthy obese control group. To keep the focus of the systematic review on overweight and obese individuals, studies that involved pregnant women and back pack loading were also excluded. Back pack loading is normally only for short periods of time so adjustments in gait may not be made (Fouad, Bastiaanse, & Dietz, 2001). Pregnancy may induce changes similar to gait in obese individuals (Branco, Santos-Rocha, Aguiar, Vieira, & Veloso, 2013) but post-pregnancy the changes return to normal (Gilleard, 2013).

Interventions to be included were diet, exercise, diet and exercise combined and surgery. These were with or without a comparison of healthy participants, and with pre and post intervention measures. An accepted length of time for interventions to give significant weight loss changes in participants undergoing exercise and diet intervention is 12 – 15 weeks (W. C. Miller, Koceja, & Hamilton, 1997). With low energy intake diets, initial body mass loss is ~2 kg/week over four weeks, 9 – 26 kg over 4-20 weeks and ~1 – 1.5 kg/week over 20 weeks (Asher, et al., 2013).

Outcome measures that the systematic review would focus on are: gait temporal-spatial parameters; lower limb kinematics and kinetics during gait. As well as having a weight loss intervention. Physiological and psychological (through questionnaires, interviews, etc.) outcomes would not be focussed on as this is primarily a biomechanical systematic review. Commentaries, reviews, case studies and qualitative studies have been excluded from the searches.

Table 2: Inclusion and exclusion criteria

	Inclusion	Exclusion
Population	Male	children
	Female	teenagers
	age 18-65	elderly >65
	obese BMI >30 (25)	pregnant
	Healthy	disabled
		osteoarthritis
		Diabetes
Intervention	diet and exercise	backpack load
	Surgery	
	pre vs. post	
	obese vs. normal	
	12 week	
Comparative Intervention	control group	
	healthy weight	
Outcomes	Gait	quality of life questionnaire
	Balance	treadmill gait
	functional tests	physiological outcomes
Types of Studies	RCT	commentaries
	clinical controlled trials	Reviews
		case studies
		qualitative studies

Search terms were listed to cover all aspects of the research focus. Synonyms and related terms were listed for the main areas of the research focus. Truncations were used for terms which could be plural or used different endings in the literature. The terms used for the database searches are shown in Table 3, with the Boolean phrase OR used between each search term to expand the search area. The Boolean phrase AND was used between each group of terms to focus the search and cover all aspects of the research question. The Boolean phrase NOT was used to exclude terms from the exclusion criteria. The searches were limited to include only human subjects, English language and original articles in peer reviewed journals. EMG was not included as additional subcutaneous fat effects data from obese individuals (Bartuzi, Tokarski, & Roman-Liu, 2010; Cooper, Herda, Vardiman, Gallagher, & Fry, 2014). Power and pressure data was not included as these were not part of the systematic review focus and there was very little literature available for weight loss in obese individuals.

The databases searched were Scopus and SPORTDiscus, Academic Search Premier, CINAHL Plus and MEDLINE through EBSCOHost, and Embase through Ovid SP. These databases were chosen as they cover sport science, fitness, health and medical related journals. Web of Science and JSTOR were not included in the searches as the journals covered by these databases had covered a broader range of topic areas. The full text was searched in Scopus, SPORTDiscus and CINAHL Plus. Academic Search Premier, MEDLINE and Embase were searched for title, abstract and keywords due to a large number of records found when searching the full text. The search criteria was also refined to get a more manageable number of hits to analyse through limiting the date range to articles published after 1990 when biomechanics and gait analysis techniques and equipment started to become more sophisticated and technologically advanced (Simon, 2004; Whittle, 1996). Articles found that were published in the 1980s came to a total of 6691, articles found published during the 1990s had between 1000 – 3000 articles for each year.

Table 3: Search terms used for all database searches.

Population	**Intervention**	**Outcome Measures**	**Exclude**
obes* OR overweight OR adipos* OR adult* OR BMI OR fat mass OR human OR body mass index OR fat OR body mass OR body weight OR body fat OR fat free mass	weight loss OR weight management OR diet* OR exercise OR training OR physical activity OR aerobic OR strength training OR resistance training OR walk* OR jog OR low calorie OR energy deficient OR surgery OR bariatric OR calorie restriction OR strength OR resistance OR very low calorie OR low energy OR physical exercise OR weight reduction OR exercise intensity OR nutrition* OR treatment	gait* OR walk* OR balance OR postur* OR function* OR sit to stand OR quality of life OR ankle OR knee OR hip OR angle OR moment OR GRF OR kinetic* OR kinematic* OR force OR biomechanic* OR torque OR load OR strength OR locomotion OR health OR weight loss OR muscle strength OR body composition OR activities of daily living OR lower limb OR lower extremity	child* OR adolescent* OR teen* OR elderly OR older adults OR osteoarthritis OR diabetes OR mobility disorders OR back pack loading OR pregnant OR osteoporosis OR osteopenia OR animal*

The hits from each search are shown in Table 4. References and abstracts of all journals found in the search results were exported to Endnote X4 (Thomson Reuters, Philadelphia, PA, USA). Duplicate references were deleted in Endnote and the total number of titles to analyse came to 192031.

The article titles were reviewed and articles that did not meet the inclusion criteria (Table 2), were unrelated to the research focus (Table 1) or duplicated were discarded. In addition to the comorbidities listed in Table 2 as part of the exclusion criteria, journal titles that included animals, HIV, cerebral palsy, spinal cord injury, liver function, renal function, urinary incontinence, gall stones and sleep apnea were regarded as irrelevant and excluded from further analysis.

Table 4: Numbers of journals found from each database search.

Database	Total Hits	Duplicates Removed	Articles to Review by Title and Abstract
Scopus	56781	2401	54380
SPORTDiscus	41719	3435	38284
Academic Search Premier	58132	3346	54786
CINAHL Plus	12060	1134	10926
MEDLINE	43578	17560	26018
Embase	17371	9734	7637
Totals	**229641**	**37610**	**192031**

In total 5053 article abstracts were included for review. Abstracts that did not include biomechanical outcome measures such as gait parameters, functional mobility or muscle strength were excluded from further analysis. Abstracts that only included weight loss (e.g. fat distribution, waist-to-hip ratio, total weight lost), psychosocial (e.g. body image perception, health related quality of life) or physiological (e.g. insulin sensitivity, plasma glucose, blood lipid, cholesterol levels, hypertension, metabolic rate) outcome measures were regarded as irrelevant.

A total of 231 journal articles were included to be read in full. The 25 full journal articles that were not found through searches on the internet were requested through the university library services for hard copies. Reference lists were checked in review articles and included articles to find additional articles that were missed from the initial search, an additional 33 journal articles were searched for and included for analysis. Information was extracted from the journals ready for analysis (Table 5). The specific outcome measures were chosen to reflect the information presented in journal articles included in the systematic review.

Table 5: Information extracted when full journal articles were read.

Journal Information	**Subject Information**	**Study Information**	**Outcome Measures**
Author Date Title	Age Gender Height Body mass BMI Number of subjects	Type of study Intervention conditions • Diet • Exercise • Surgery • Control group Duration of interventions, follow-up measurements	Gait temporal-spatial parameters • Gait velocity • Cadence • Stride/step length • Swing duration • Stance duration • Double support duration • Cycle time • Stance width Kinematics and kinetics in sagittal, frontal and transverse plane: • Mean ankle flexion during stance • Toe out angle • Knee flexion at IC • Mean knee flexion during stance • Peak knee flexion during early stance • Min knee flexion during stance • Knee flexion at TO • Hip flexion at IC • Mean flexion during stance • ROM in swing phase • Ankle plantar flexor angular impulse • Peak knee extensor moment during early stance • Knee extensor angular impulse in early stance • Peak knee flexor moment • Knee abductor moment during early stance • Knee abductor moment during late stance • Peak hip extensor moment • Peak hip flexor moment • Hip extensor angular impulse • 1st Vertical load acceptance peak

			GRF - 2^{nd} Vertical thrust peak GRF - Anterior-posterior breaking peak GRF - Anterior-posterior propulsive peak GRF - Medial-lateral peak GRF - Loading response

Articles where it could not be determined from the abstract whether they were relevant to the research focus were left in and removed from the analysis later. There were a number of abstracts where weight loss interventions were used but only from fully reading articles it was determined no biomechanical data was collected. This was also the case for some review articles, letters to editors and commentaries where it was unclear what detail was involved from the abstract. Some articles that were not written in English had English translations for the abstracts only but not for the full article. On reading the full articles some were excluded, reasons for articles not being included are shown in the flowchart (Figure 2) (Moher, Liberati, Tetzlaff, & Altman, 2009).

Originally outcome measures other than gait were included in the database searches but were later removed from the research focus. Balance and pressure data was excluded from the systematic review as it was not part of the research focus. Articles where there was not enough gait data focussed mainly on functional movement outcome measures such as timed-up-and-go, chair rises and stair climbing. These outcome measures did not give enough kinematic and moment information required for the research focus of the systematic review. However, studies where gait velocity could be calculated from 6MWT or 400 m walk functional gait measures were included in the systematic review.

Journal articles were included in the systematic review if they contained temporal-spatial gait parameters, lower limb kinematics and kinetics for obese individuals with a weight loss intervention. Study information and outcome measures from journal articles were recorded into results tables. The quality of the journal articles was assessed using a critical review form for quantitative studies (Law et al., 1998).

No further statistical analysis was undertaken on the includes journal articles due to the limited number of journal articles included in the systematic review that had biomechanical outcome measures other than gait velocity. There were only two included journal articles that measured joint angle and moment outcome measures, which were not completely comparable so no further statistical analysis could be completed.

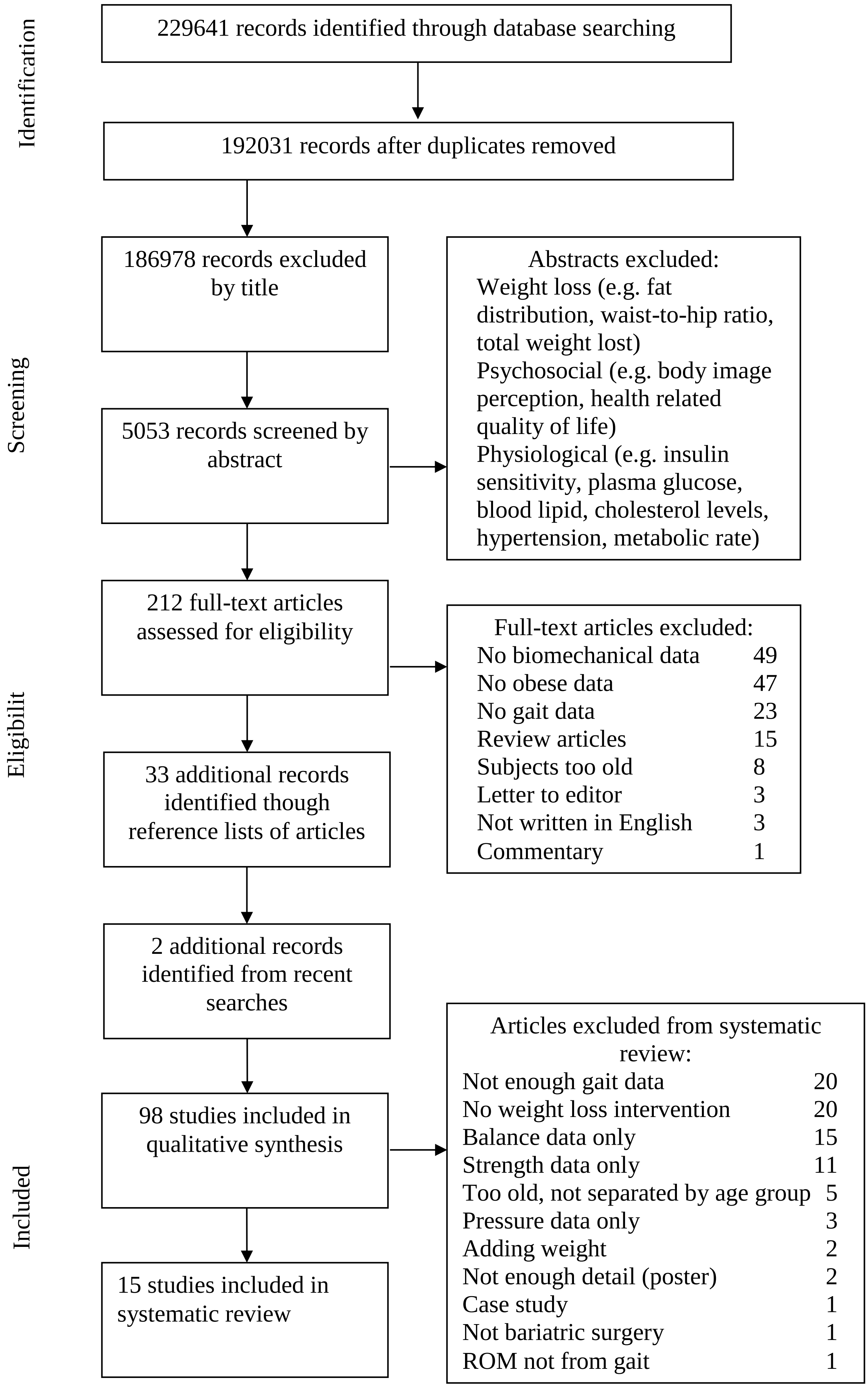

Figure 2: Process for article identification for inclusion in analysis.

4. Results

The Cochrane style flow diagram of the systematic review results in shown in Figure 2. From full text articles reviews fifteen separate studies were included in the systematic review. Table 6 shows study and subject information. The same participants were reported on in the Bragge et al. (2014) , Lyytinen, et al. (2013) and Vartiainen et al. (2012) studies so data collected for the outcome measures were combined for these publications. Twelve studies used surgery as a weight loss intervention (Bragge, et al., 2014; De Souza, et al., 2009; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Tompkins, et al., 2008; Vargas, et al., 2013; Vartiainen, et al., 2012; Vincent, Ben-David, et al., 2012), with two of these including additional exercise after surgery (Castello, et al., 2011; Stegen, et al., 2011). Five studies used diet and/or exercise as the weight loss intervention; with one using exercise only (Sarsan, et al., 2006), one using diet only (Evers Larsson & Mattsson, 2003), two using diet and exercise (Gabriel, et al., 2011; Lemoine et al., 2007) and one using diet with participants encouraged to increase physical activity levels but no set exercise programme (Plewa, et al., 2007). The intervention duration ranged from 3-weeks to 48-months, with the surgery interventions generally having longer follow-up times (3 – 12 months) and in three studies multiple follow-ups (Evers Larsson & Mattsson, 2003; Hortobagyi, et al., 2011; Tompkins, et al., 2008).

Nine studies compared the participants' baseline measurements to their post intervention measurements (Table 6) (Bragge, et al., 2014; De Souza, et al., 2009; Evers Larsson & Mattsson, 2003; Josbeno, et al., 2010; Lemoine, et al., 2007; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Plewa, et al., 2007; Tompkins, et al., 2008; Vargas, et al., 2013;

Vartiainen, et al., 2012). Four studies were randomised controlled trials comparing the weight loss intervention to a control group (Castello, et al., 2011; Gabriel, et al., 2011; Sarsan, et al., 2006; Stegen, et al., 2011). Two studies were non-randomised controlled trials, where the experimental group were undergoing surgery and were compared to a control group (Hortobagyi, et al., 2011; Vartiainen, et al., 2012).

In total 32 males and 951 females participated in all of the studies (Table 7), one study did not specify the gender of the 10 participants (Hortobagyi, et al., 2011). The age of participants ranged from 18 – 64 years old. The mean age of participants ranged between 34.7 – 57.1 years old. The mean BMI was over 30 kg/m^2 for all participants, although participants undergoing surgery interventions had higher mean baseline BMI ranging from 40.4 – 51.1 kg/m^2 due to individuals having to be morbidly obese (BMI > 40 kg/m^2 or BMI > 35 kg/m^2 with at least two comorbidities) before surgery is considered (Asher, et al., 2013; Silver, et al., 2006). The mean body mass before weight loss intervention ranged between 81.2 – 274.8 kg, surgery intervention studies included participants with higher initial mean body mass (above 114.3 kg). Longer intervention duration (> 7 months) had more participants dropout compared to shorter intervention duration (3 months). Although for total participant compliance, surgery interventions had higher participant dropouts as the initial participant numbers were lower.

Table 6: Intervention and method details for included studies.

Author and Date	Type of Study	Intervention	Follow-Up Time	Measurement Method [Data Collected]	Group	Participants in Group	Participants (Completion: Dropout)
Castello et al. (2011)	Randomised controlled trial	Surgery and exercise Aerobic exercise 1 hr, 3 times/week after Roux-en-Y gastric bypass	4 months	6MWT	Surgery and Exercise	16	11:5
					Surgery only control	16	10:6
De Souza et al. (2009)	Longitudinal (pre/post)	Surgery Roux-en-Y gastric bypass	7-12 months	6MWT	-	51	49:2
Evers Larsson et al. (2003)	Londitudinal (pre/post)	Diet 330-420 or 1600 kcal/day for 8-12 weeks then 1600 kcal/day for 52-104 weeks	12 and 64 weeks	speedometer (Walking velocity)	-	57	43:14
Gabriel et al. (2011)	Randomised controlled trial	Diet and physical activity changes	48 months	400m walk	Lifestyle change	253	222:31
					Health education control	255	234:21
Hortobagyi et al. (2011)	non-randomised	Surgery Roux-en-Y	7 (T1) and 12 (T2) months	8 Qualisys cameras 120	Weight loss	20	10:10

	control	gastric metabolic surgery		Hz, AMTI force platform 960 Hz (3D kinematic and kinetic gait data)	Healthy weight control	10	10:0
Josbeno et al. (2010)	Longitudinal (pre/post)	Surgery Laparoscopic gastric bypass	3 months	6MWT	-	20	18:2
Lemoine et al. (2007)	Longitudinal (pre/post)	Diet and exercise 1200-1600 kcal/day 45 min cycle and 25 min walking 6 times/week	3 weeks	6MWT	Pre-menopausal	13	13:0
					Postmenopausal	27	27:0
Maniscalco et al. (2006)	Longitudinal (pre/post)	Surgery Laparoscopic adjustable gastric banding	12 months	6MWT	-	15	15:0
Plewa et al. (2007)	Longitudinal (Pre/Post)	Diet (and exercise) 1000-1200 kcal/day diet Increase exercise to 3-5 times/week for 30-60 mins	12 weeks	Instrumented walkway (Temporal-spatial gait parameters)	-	52	52:0
Sarsan et al. (2006)	Randomised controlled trial	Exercise Aerobic	12 weeks	6MWT	Aerobic exercise	26	20:6

		exercise – increasing intensity 15-45 mins 3-5 days/week Resistance exercise – increasing intensity 1-3 sets (10 reps) 3 days/week			Resistance exercise	26	20:6
					No exercise control	24	20:4
Stegen et al. (2011)	Randomised controlled trial†	Surgery and exercise 75 mins 3 times/week for 12 weeks after gastric bypass	4 months	6MWT	Surgery and exercise	10	8:2
					Surgery only control	9	7:2
Tompkins et al. (2008)	Longitudinal (pre/post)	Surgery Gastric bypass	3 and 6 months	6MWT	-	30	25:5
Vargas et al. (2013)	Longitudinal (pre/post)	Surgery Roux-en-Y gastric bypass	3 months	6MWT	-	67	67:0
Vartiainen et al. (2012) and Bragge et al. (2014)	Longitudinal (Pre/Post)	Surgery Roux-en-Y gastric bypass	8.8 months	6 Basler cameras 100 Hz, 2 AMTI force platforms 1000 Hz (3D kinematic and kinetic gait data)	-	18	13:5

Lyytinen et al. (2013)				6MWT, goniometer (ROM)		18	16:2
Vincent et al. (2012)	non-randomised control	Surgery Laparoscopic roux-en-Y gastric bypass surgery or gastric banding	3 months	Gait rite pressure mat (Temporal-spatial gait parameters)	Surgery	25	25:0
					No surgery obese control	20	20:0

†Participants chose the intervention group they were in.

Where there was no explicit follow-up body mass data but results were available on amount of body mass change (delta); calculated values of post follow-up body mass appear in Table 7. Total mass lost was calculated from baseline and follow-up data. The mean body mass loss ranged from 0.3 kg for a health education control group (Gabriel, et al., 2011) to a maximum of 75.0 kg observed six months after gastric bypass surgery (Tompkins, et al., 2008). Amongst the dietary and exercise interventions, body mass loss ranged from 0.3 – 14.7 kg, with a significant reduction in body mass reported in four studies (Evers Larsson & Mattsson, 2003; Lemoine, et al., 2007; Plewa, et al., 2007; Sarsan, et al., 2006). Surgical weight loss interventions gave a significant reduction in body mass ranging from 19.4 – 75.0 kg (Bragge, et al., 2014; Castello, et al., 2011; De Souza, et al., 2009; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, et al., 2013; Vartiainen, et al., 2012). Where there were multiple follow-ups the body mass continued to reduce significantly from baseline measurements for surgery interventions (Hortobagyi, et al., 2011; Tompkins, et al., 2008). However, for diet intervention studies at the second follow-up participants had regained body mass (Evers Larsson & Mattsson, 2003). Among exercise interventions (prescribed following bariatric surgery) one study found surgery only participants lost more body mass (Stegen, et al., 2011) and one study found no difference in the amount of body mass lost between the two groups (Castello, et al., 2011).

Baseline mean BMI ranged from 30.6 ± 3.8 to 51.1 ± 9.2 kg/m^2 with a significant reduction evident in all studies (post intervention BMI ranged from 28.2 ± 8.1 to 40.4 kg/m^2) (Table 8). The largest change was measured by De Souza et al. (2009) 7 – 12 months after gastric bypass surgery (from 51.1 ± 9.2 to 28.2 ± 8.1 kg/m^2), although the participants remained in either overweight or obese BMI category. There were no interventions that ended with participants in the normal BMI range (18.5 – 25 kg/m^2) within the timeframe of the study (WHO, 2006).

Gait velocity was the simplest outcome measure to compare across all studies as it could be calculated from functional walking tests if it was not measured directly. Nine studies measured gait through functional walking tests (6MWT or 400 m walk) (Table 8). Gait velocity was calculated from distance/time data provided from 6MWT or time taken to walk 400 m. Five studies measured gait velocity directly, through a speedometer (Evers Larsson & Mattsson, 2003), timing gates (Hortobagyi, et al., 2011; Vartiainen, et al., 2012), and an instrumented walkway (Plewa, et al., 2007; Vincent, Ben-David, et al., 2012).

The improvement in gait velocity ranged from 0.02 – 0.43 m/s. After surgery intervention the mean improvement in gait velocity was 0.22 m/s (range 0.04 – 0.42 m/s), after diet and exercise intervention the mean improvement in gait velocity was 0.12 m/s (range 0.2 – 0.43 m/s). In studies with gait velocity data collected directly there was a significant improvement from baseline to follow-up, with an improvement range of 0.05 – 0.15 m/s. Overall, more improvement was evident within two surgical intervention (0.05 – 0.15 m/s) studies (Hortobagyi, et al., 2011; Vincent, Ben-David, et al., 2012) compared to two studies evaluating diet and exercise intervention (0.05 – 0.08 m/s) (Evers Larsson & Mattsson, 2003; Plewa, et al., 2007).

There was a significant increase in distance walked in the 6MWT for all studies (Table 8), ranging from 340 – 600 m at baseline assessment and improving to 410 – 644 ± 104.22 m after weight loss intervention. The control groups showed no significant improvement in the distance walked or gait velocity (Castello, et al., 2011; Gabriel, et al., 2011; Sarsan, et al., 2006; Stegen, et al., 2011; Vincent, Ben-David, et al., 2012).

Four studies measured further temporal-spatial gait parameters (Table 9). After the weight loss intervention; walking at PWS showed a significant increase in gait velocity and swing time, a significant increase in step length (Vincent, Ben-David, et al., 2012), and a significant reduction in double support, stance time and cycle time (Plewa, et al., 2007). Two studies (one surgical and one dietary and exercise intervention) reported a significant increase in stride length (Hortobagyi, et al., 2011; Plewa, et al., 2007) and one study reported a significant increase in cadence (Plewa, et al., 2007). All other studies reporting stride length and cadence did not show significant increase.

In the Vincent et al. (2012) study, the obese control group had no significant changes between the pre and post measurements compared to the experimental group that underwent a surgery intervention in which gait velocity, step length and swing time had significant improvements. In the investigations incorporating walking at fixed gait velocities there were no significant improvements in stride length, swing time and double support duration. Vartiainen et al. (2012) showed a significant decrease in stance width following surgically induced weight loss. However Vincent et al. (2012) reported a non-significant reduction in stance width.

Table 7: Subject characteristics for included studies. Where available values are mean ± SD.

Author and Date	Intervention and Follow-up Time	Group	Age of Subjects (years) [Range]	Number of Participants (Gender M:F)	Pre Intervention Body Mass (kg)	Post Intervention Body Mass (kg)	Total Mass Lost (kg)	Pre Intervention BMI (kg/m^2)	Post Intervention BMI (kg/m^2)
Castello et al. (2011)	Surgery + exercise / Surgery 4 months	Surgery and Exercise	38.0 ± 4.0 (20-45)	0:11	117.0 ± 4.0*	94.0 ± 4.0*	23.0 #	45.64 ± 1.51*	36.82 ± 1.28*
		Surgery only control	36.0 ± 4.0 (20-45)	0:10	117.0 ± 6.0*	94.0 ± 5.0*	23.0 #	44.46 ± 0.96*	35.71 ± 0.92*
De Souza et al. (2009)	Surgery 7-12 months	-	40.9 ± 9.2	7:44	-	-	-	51.1 ± 9.2*	28.2 ± 8.1*
Evers Larsson et al. (2003)	Diet 12 and 64 weeks	-	46.2 ± 10.0 (23-64)	0:43	106.5 ± 12.7*	91.8 ± 11.7 (12 weeks)* 96.3 ± 12.8 (64 weeks)*	14.7 (12 weeks) # 10.2 (64 weeks) #	37.8 ± 3.4*	32.4 ± 3.6 (12 weeks)* 34.1 ± 3.9 (64 weeks)*
Gabriel et al. (2011)	Diet + exercise education 48 months	Lifestyle change	56.9 ± 2.94	0:253	81.2 #	78.3 #	2.9 #	30.6 ± 3.8*	29.5 ± 4.2*
		Health education control	57.1 ± 2.94	0:255	82.2 #	81.9 #	0.3 #	30.9 ± 3.8	30.9 ± 4.2
Hortobagyi et al. (2011)	Surgery 7 (T1) and 12 (T2) months	weight loss	42.8 ± 10.6	10	125.7 ± 26.6*	91.7 (7 months) # 83.5 ± 20.3 (12 months)*	34.0 ± 9.3 (7 months)* 42.2 ± 14.1 (12	43.2 ± 6.5*	31.7 (7 months) # 28.9 (12 months) #

							months)*		
		Healthy weight control	43.6 ± 10.7	-	62.3 ± 11.7	-	-	21.8 ± 2.8	-
Josbeno et al. (2010)	Surgery 3 months	-	41.6 ± 9.8	2:18	-	-	24.4 ± 5.6	46.9 ± 6.3*	37.4 ± 5.7*
Lemoine et al. (2007)	Diet + exercise 3 weeks	Pre-menopausal	39 ± 5 (30-45)	0:13	96.9 ± 11.3	94.1 #	2.8 ± 0.25*	36.4 ± 3.3*	35.3 #
		Postmenopausal	56 ± 4 (49-64)	0:27	93.9 ± 11.8	91.59 #	2.31 ± 0.19*	36.7 ± 3.8*	35.8 #
Maniscalco et al. (2006)	Surgery 12 months	-	34.7 ± 12.7	0:15	114.3 ± 11.6*	86.6 ± 10.4*	27.2 #	42.1 ± 4.1*	31.9 ± 3.6*
Plewa et al. (2007)	Diet (+exercise) 12 weeks	-	37.3 ± 11.2 (18-57)	0:52	97.7 ± 12.8	90.4 ± 12.8*	7.3 #	36.5 ± 4.8*	34.1 ± 4.8*
Sarsan et al. (2006)	Aerobic exercise / Resistance exercise / control 12 weeks	Aerobic exercise	41.65 ± 7.62 (20-60)	0:20	87.52 ± 11.68*	84.00 ± 12.02*	3.52 ± 2.84*	35.38 ± 4.98*	33.94 ± 4.95*
		Resistance exercise	42.50 ± 10.07 (20-60)	0:20	83.77 ± 9.49*	80.95 ± 9.52*	2.82 ± 3.54*	33.73 ± 2.92*	32.59 ± 2.95*
		No exercise control	43.60 ± 6.46 (20-60)	0:20	86.82 ± 11.27	86.40 ± 11.46	0.42 ± 2.04	35.54 ± 3.67	35.36 ± 3.69
Stegen et al. (2011)	Surgery + exercise / Surgery 4 months	Surgery and exercise	39.9 ± 9.9	1:7	130.8 ± 17.8*	108.1 #	22.7 ± 5.7*	45.3 ± 2.7*	37.2*
		Surgery only control	43.1 ± 5.6	3:4	126.5 ± 24.7*	99.9 #	26.6 ± 14.6*	40.4 ± 8.1*	32.1*
Tompkins et al.	Surgery 3 and 6	-	44 ± 6.3 (31-58)	2:28	274.8 ± 51.8*	224.2 ± 45.2 (3	50.6 (3 months) #	45.5 ± 6.9*	35.7 ± 9.7 (3 months)*

(2008)	months					months)* 199.8 ±41.0 (6 months)*	75.0 (6 months) #		30.1 ± 10.4 (6 months)*
Vargas et al. (2013)	Surgery 3 months	-	38 ± 10 (20-50)	6:61	132.61 ± 23.66*	104.29 ± 23.13*	28.31 ± 16.44*	50.45 ± 8.5*	38.74 ± 9.23*
Vartiainen et al. (2012), Bragge et al. (2014), Lyytinen et al. (2013)	Surgery 8.8 months	-	45.1 ± 9.5 (30-63)	3:13	127.0 ± 19.7*	99.7 ± 17.5*	27.3 ± 8.9*	44.0 ± 5.3*	34.5 ± 4.8*
Vincent et al. (2012)	Surgery 3 months	Surgery	41 ± 11	5:20	125.5 ± 20.7	106.1 ± 18.7	19.4 ± 7.7	47 ± 7*	40.4 #
		No surgery obese control	50 ± 7	3:17	115 ± 22	-	-	42 ± 6	-

*Significant differences between values (from articles P<0.05), # Calculated values.

Table 8: Gait velocity and functional walking test outcome measures. Where available values are mean ± SD. For functional walking tests velocity is calculated from distance data from 6MWT or time taken for 400m walk.

Author and Date	Intervention and Follow-up Time	Group	Pre Intervention Gait Velocity (m/s)	Post Intervention Gait Velocity (m/s)	Pre Intervention 6MWT Distance (m)	Post Intervention 6MWT Distance (m)	Pre Intervention 400m Walk (s)	Post Intervention 400m Walk (s)
Castello et al. (2011)	Surgery + exercise / Surgery 4 months	Surgery and Exercise	1.33 #	1.47 #	477.9 ± 22.9*	527.6 ± 17.7*	-	-
		Surgery only control	1.37 #	1.41 #	492.6 ±21.1	509.0 ± 12.5	-	-
De Souza et al. (2009)	Surgery 7-12 months	-	1.06 #	1.30 #	381.9 ± 49.3*	467 ± 40.3*	-	-
Evers Larsson et al. (2003)	Diet 12 and 64 weeks	-	1.19*	1.27 (12 weeks)* 1.25 (64 weeks)*	-	-	-	-
Gabriel et al. (2011)	Diet + exercise education 48 months	Lifestyle change	1.28 #	1.30 #	-	-	311.6 ± 37.0 s*	308.7 ± 41.0 s*
		Health education control	1.27 #	1.25 #	-	-	314.7 ± 37.0 s	320.5 ± 41.0 s
Hortobagyi et al. (2011)	Surgery 7 (T1) and 12 (T2) months	weight loss	1.30 ± 0.14*	1.35 ± 0.18 (7 months)* 1.45 ± 0.17 (12 months)*	-	-	-	-
		Healthy weight control	1.50 – standard velocity	1.52 ±0.01	-	-	-	-
Josbeno et al.	Surgery	-	1.09 #	1.24 #	393 ± 62.08*	446 ± 41.39*	-	-

(2010)	3 months							
Lemoine et al. (2007)	Diet + exercise 3 weeks	Pre-menopausal	1.59 #	1.63 #	571 †	588 †	-	-
		Postmenopausal	1.67 #	1.69 #	600 †	610 †	-	-
Maniscalco et al. (2006)	Surgery 12 months	-	1.32 #	1.74 #	475.7*	626.3*	-	-
Plewa et al. (2007)	Diet (+exercise) 12 weeks	-	1.07 ± 0.2*	1.12 ± 0.22*	-	-	-	-
Sarsan et al. (2006)	Aerobic exercise / Resistance exercise / control 12 weeks	Aerobic exercise	1.36 #	1.79 #	490.5 ± 75.04*	644.7 ± 104.22*	-	-
		Resistance exercise	1.35 #	1.67 #	484.4 ± 93.79*	602.7 ± 99.64*	-	-
		No exercise control	1.29 #	1.30 #	462.80 ± 72.96	469.10 ± 79.19	-	-
Stegen et al. (2011)	Surgery + exercise / Surgery 4 months	Surgery and exercise	1.35 #	1.49 #	485.9 ± 28.8*	537.6 ± 40.6*	-	-
		Surgery only control	1.32 #	1.40 #	475.2 ± 58.8	505.2 ± 86.8	-	-
Tompkins et al. (2008)	Surgery 3 and 6 months	-	1.15 #	1.40 (3 months) # 1.53 (6 months) #	414.1 ± 103.7*	505.2 ± 98.0/ (3 months)* 551.5 ± 101.2 (6 months)*	-	-
Vargas et al. (2013)	Surgery 3 months	-	1.23 #	1.39 #	405.34 ± 92.26*	500.1 ± 111.63*	-	-
Vartiainen et al. (2012) and Bragge	Surgery 8.8 months	-	Gait velocities set at 1.20 and 1.50		-	-	-	-

et al. (2014)								
Lyytinen et al. (2013)			1.39 #	1.56 #	500 †	560 †		
Vincent et al. (2012)	Surgery 3 months	Surgery	1.08 ± 0.17*	1.23 ± 0.17*	-	-	-	-
		No surgery obese control	0.86 ± 0.32	0.86 ± 0.34	-	-	-	-

†Values taken from graphs, *Significant differences between values (from articles P<0.05), # Calculated values.

Table 9: Temporal spatial outcome measures in surgical and diet and exercise weight loss intervention studies. Where available values are mean ± SD.

Author and Date	Intervention and Follow-up Time	Time of Testing	Gait Velocity (m/s)	Cadence (step/min)	Stride Length (m)	Step Length (m) [average of R and L]	Swing Duration (%)	Stance Duration (%)	Double Support Duration (%)	Stance Width (m)	Cycle Time (s)
Hortobagyi et al. (2011)	Surgery	Pre	1.30 ± 0.14*	112 ± 8.9	1.38 ± 0.11*	-	35.3 ± 1.9*	64.7 #	-	-	-
	7 months	T1	1.35 ± 0.18*	111 ± 8.6	1.44 ± 0.15*	-	36.6 ± 1.6*	63.4 #	-	-	-
	12 months	T2	1.45 ± 0.17*	116 ± 7.5	1.49 ± 0.18*	-	37.8 ± 2.0*	62.2 #	-	-	-
Plewa et al. (2007)	Diet (+exercise)	Pre	1.07 ± 0.2*	105.25 ± 10.47*	1.21 ± 0.14*	-	33.99 ± 1.93*	65.88 ± 1.92*	15.99 ± 1.98*	-	1.15 ± 0.12*
	12 weeks	Post	1.12 ± 0.22*	107.78 ± 11.72*	1.24 ± 0.15*	-	34.48 ± 2.0*	65.37 ± 2.04*	15.52 ± 2.02*	-	1.13 ± 0.13*
Vartiainen et al. (2012) and Bragge et al. (2014)	Surgery	Pre slow	1.2	-	1.29 ± 0.09	-	37.6 ± 1.3	62.4 #	14.6 ± 1.8	0.12 ±0.03*	-
	8.8 months	Post slow	1.2	-	1.30 ± 0.10	-	37.8 ± 1.3	62.2 #	14.1 ± 0.9	0.09 ± 0.03*	-
		Pre fast	1.5	-	1.42 ± 0.09	-	40.0 ± 1.0	60.0 #	13.2 ± 1.3	0.13 ± 0.02*	-
		Post fast	1.5	-	1.42 ± 0.08	-	40.1 ± 1.8	59.9 #	12.9 ± 1.3	0.09 ± 0.02*	-
Vincent et al.	Surgery	Pre surgery	1.08 ± 0.17*	103 ± 12	1.119 ± 0.335	0.602 ± 0.063*	33.4 ± 1.7*	66.6 #	-	0.13 ± 0.045	-

(2012)	3 months	Post-surgery	1.23 ± 0.17*	113 ± 24	1.131 ± 0.2	0.65 ± 0.106*	36.0 ± 1.5*	64.0 #	-	0.105 ± 0.042	-
		Pre control	0.86 ± 0.32	95 ± 17	1.139 ± 0.294	0.57 ± 0.147	32.2 ± 5.2	67.8 #	-	0.129 ± 0.067	-
		Post control	0.86 ± 0.34	100 ± 19	1.18 ± 0.271	0.593 ± 0.135	33.2 ± 3.9	66.8 #	-	0.125 ± 0.05	-

*Significant differences between values (from articles $P<0.05$), # Calculated values.

Three-dimensional gait analysis is particularly difficult in obese individuals due to the accuracy of marker placement on anatomical landmarks under excess subcutaneous fat mass (Borhani, et al., 2013; Lerner, et al., 2014; Menegoni, Vismara, et al., 2009; M. Smith, et al., 2013). Consequently, only Hortobagyi et al. (2011) and Vartiainen et al. (2012) reported outcome measures on lower limb sagittal plane joint angular displacement (Table 10) and moments, GRF (Table 11) and frontal plane knee moments (Table 12). Vincent et al. (2012) only reported toe out angle as they collected data on a gait rite pressure mat; but there is no kinematic data from the instrumented walkway used by Plewa et al. (2007) . Lyytinen et al. (2013) measured knee and hip ROM but data is not included as it was measured with a goniometer and not through gait analysis.

The included studies have used a range of walking speeds within their protocol. Hortobagyi et al. (2011) and Vincent et al. (2012) measured the obese individuals at their PWS. Whereas Vartiainen et al. (2012) set the subjects a walking velocity of 1.2 m/s. Hortobagyi et al. (2011) and Vartiainen et al. (2012) also measured obese individuals walking at a faster velocity of 1.5 m/s to give an indication of how obese individuals adapted their gait to walking at a velocity similar to that of healthy adults. Limited comparisons can be made on angular displacement (Table 10) and joint moment (Table 12) data across studies, due to data being collected at different points of the gait cycle, lack of inclusion of joint data or lack of measurements in all planes of movement.

Hortobagyi et al. (2011) found a significant reduction in mean ankle dorsi flexion during stance phase from the pre surgery measurements to the follow-up measurements at both velocities (Hortobagyi, et al., 2011). In a separate study, with assessment of the transverse plane there was a non-significant reduction in toe out angle after surgery (Vincent, Ben-David, et al., 2012).

The peak knee flexion angles during early stance phase (in the sagittal plane) show different outcomes after surgery. Hortobagyi et al. (2011) showed a significant increase in peak flexion at the second follow-up measurement for PWS with a non-significant increase at 1.5 m/s, whereas Vartiainen et al. (2012) show a non-significant decrease in peak flexion at 1.2 and 1.5 m/s. The knee flexion at IC and TO was similar after surgery when walking at 1.5 m/s, but at 1.2 m/s knee flexion at IC was reduced non-significantly after surgery (Vartiainen, et al., 2012). Lyytinen et al. (2013) found knee flexion increased significantly after surgery but changes in knee extension were non-significant.

Hip ROM in swing phase increased significantly for the second follow-up measurement at PWS although there was a non-significant increase at 1.5 m/s (Hortobagyi, et al., 2011). Mean hip flexion during stance phase increased non significantly (Hortobagyi, et al., 2011) and hip flexion at IC reduced significantly (Vartiainen, et al., 2012) after surgery for both gait velocities. Lyytinen et al. (2013) found external hip rotation and left leg internal hip rotation increased significantly after surgery but the increase in right leg internal hip rotation was non-significant.

Table 10: Joint angular displacement outcome measures in three surgical weight loss intervention studies. All values Mean ± SD.

Author, Date, Intervention and Follow-up time	**Joint**	**Angular Displacement Data (deg) Walking at PWS/1.2 m/s**	**Angular Displacement Data (deg) Walking at 1.5 m/s**
Hortobagyi et al. (2011) Surgery (PWS) T0 – baseline – 1.30 m/s T1 - 7 months – 1.35 m/s T2 - 12 months – 1.45 m/s	Ankle (negative is dorsi flexion)	Mean flexion during stance T0 -3.6 ± 2.8* T1 -1.5 ± 2.6* T2 -2.1 ± 2.4*	Mean flexion during stance T0 -3.6 ± 2.3* T1 -1.3 ± 2.6* T2 -1.8 ± 2.2*
	Knee (negative is flexion)	Mean flexion during stance T0 -9.04 ± 3.9 T1 -9.0 ± 3.9 T2 -9.6 ± 3.56	Mean flexion during stance T0 -9.14 ± 4.5 T1 -8.5 ± 3.6 T2 -9.4 ± 3.9
		Peak flexion during early stance T0 -11.2 ± 4.2 T1 -12.3 ± 4.6 T2 -14.7 ± 3.9*	Peak flexion during early stance T0 -13.29 ± 5.5 T1 -12.8 ± 5.0 T2 -14.8 ± 5.6
	Hip (negative is flexion)	Mean flexion during stance T0 -4.1 ± 2.2 T1 -5.3 ± 4.2 T2 -5.6 ± 2.2	Mean flexion during stance T0 -4.4 ± 2.6 T1 -5.0 ± 4.4 T2 -6.1 ± 2.6
		ROM during swing phase T0 30.2 ± 4.1 T1 32.9 ± 3.2 T2 34.1 ± 7.2*	ROM during swing phase T0 32.8 ± 4.0 T1 35.5 ± 4.4 T2 34.4 ± 7.7
Vartiainen et al. (2012) and Bragge et al. (2014) Surgery (1.2 m/s)	Ankle	No data presented	No data presented
	Knee	Flexion at IC Pre -13 ± 6 Post -10 ± 7	Flexion at IC Pre -14 ± 8 Post -14 ± 7

8.8 months		Peak flexion during early stance Pre -22 ± 5 Post -19 ± 5	Peak flexion during early stance Pre -24 ± 7 Post -22 ± 6
		Min flexion during stance Pre 1 ± 9 Post 0 ± 7	Min flexion during stance Pre 5 ± 9 Post 2 ± 7
		Flexion at TO Pre -38 ± 1 Post -38 ± 1	Flexion at TO Pre -40 ± 1 Post -40 ± 2
	Hip	Flexion at IC Pre -32 ± 6* Post -26 ± 4*	Flexion at IC Pre -32 ± 7* Post -27 ± 5*
Vincent et al. (2012) Surgery (PWS) Baseline – 1.08 m/s 3 months – 1.23 m/s	Ankle	Toe out angle Pre surgery L 6.0 ± 5.0, R 7.4 ± 3.1 Post-surgery L 5.5 ± 6.7, R 5.3 ± 6.2	No data collected

*Significant differences between values (from articles P<0.05).

The absolute values for GRF (Table 11) and joint moments (Table 12) are used to give an indication of the loading forces occurring at the joints of obese participants during walking gait and used to determine impacts on the musculoskeletal system and the development of musculoskeletal disorders (Anandacoomarasamy, et al., 2008; Wearing, et al., 2006b). After body mass reduction, there is a significant decrease in absolute GRF for the vertical, anterior-posterior (Hortobagyi, et al., 2011) and medial-lateral (Bragge, et al., 2014) directions and a reduction in the rate of the loading response (Bragge, et al., 2014; Hortobagyi, et al., 2011). When normalised to body mass the values for anterior-posterior and loading response (values not shown) were not significant after surgery (T2) when compared to lean individuals (Hortobagyi, et al., 2011).

At a faster gait velocity the absolute GRF values are slightly greater. Even as PWS increased the absolute GRF reduced significantly after surgery (Hortobagyi, et al., 2011). When normalised to body mass there was no significant change in the vertical and anterior-posterior GRF and rate of loading at the fast gait velocity (Hortobagyi, et al., 2011).

To take body mass differences into account, normalised moments are used for a comparison between normal healthy weight individuals and obese individuals (Sheehan & Gormley, 2012). Limited comparisons can be made on the normalised moments (Table 13) as Hortobagyi et al. (2011) normalised to % body mass and height and Vartiainen et al. (2012) normalised to body mass and height. Only Hortobagyi et al. (2011) presented ankle data, where the absolute plantar flexor angular impulse showed significant reduction after surgery but no significant difference when normalised (to % body mass and height).

Table 11: GRF outcome measures in two surgical weight loss intervention studies. Where available values are mean ± SD.

Author, Date, Intervention and Follow-up time	**GRF**	**GRF (N)** **Walking at PWS/1.2 m/s**	**GRF (N)** **Walking at 1.5 m/s**
Hortobagyi et al. (2011) Surgery (PWS) T0 – baseline – 1.30 m/s T1 - 7 months – 1.35 m/s T2 - 12 months – 1.45 m/s	Vertical (first load acceptance peak)	T0 1320 ± 309* T1 964 ± 250* T2 924 ± 264*	T0 1398 ± 309* T1 1012 ± 221* T2 926 ± 223*
	Anterior posterior (breaking force)	T0 -239 ± 56* T1 -190 ± 59* T2 -188 ± 67*	T0 -277 ± 80* T1 -211 ± 60* T2 -192 ± 51*
	Loading response (N/s)	T0 7660 ± 3044* T1 5693 ± 2143* T2 6090 ± 2031*	T0 9021 ± 2391* T1 6655 ± 1170* T2 6250 ± 1094*
Vartiainen et al. (2012) and Bragge et al. (2014) Surgery (1.2 m/s) 8.8 months	Vertical (first load acceptance peak)	Pre 1305 ± 188* Post 1024*#	Pre 1400 ± 222* Post 1106*#
	Vertical (second thrust peak)	Pre 1251 ± 169* Post 1025*#	Pre 1224 ± 172* Post 998*#
	Anterior posterior (braking force)	Pre 201 ± 43.4* Post 162.4*#	Pre 235 ± 60.7* Post 186.5*#
	Anterior posterior (propulsive force)	Pre 208 ± 29.5* Post 171.3*#	Pre 239 ± 43.7* Post 190*#
	Medial lateral	Pre 80.3 ± 25.2* Post 52.7*#	Pre 88.7 ± 24.8* Post 60.8*#
	Loading response (kN/s)	Pre 61.3 ± 24.2* Post 47.9*#	Pre 88.1 ± 22.8* Post 70*#

*Significant differences between values (from articles P<0.05), # Calculated values.

Vartiainen et al. (2012) found absolute peak knee flexor moment reduced significantly after surgery but no significant reduction when normalised. Knee extensor moment absolute values reduced non-significantly after surgery but had a non-significant increase for values normalised to body mass and height (Vartiainen, et al., 2012). Hortobagyi et al. (2011) found a significant increase in the normalised peak knee extensor moments at PWS. There was non-significant reduction in absolute peak knee extensor moments (Hortobagyi, et al., 2011). At the fast gait velocity the normalised peak knee extensor moments increased non-significantly. Absolute knee extensor angular impulse in early stance phase had an overall non-significant reduction but a non-significant increase when normalised (Hortobagyi, et al., 2011). There was a significant reduction in initial peak acceleration and peak to peak acceleration in both axial and shear direction after surgery (Bragge, et al., 2014).

In the frontal plane, abductor moment during early stance phase reduced significantly after surgery for absolute values (but with non-significant increase for values normalised to body mass and height) except for values from Vartiainen et al (2012) at fast gait velocity (1.5 m/s) showed a significant increase. At the faster gait velocity, the baseline values were higher but closer to the slower velocity values after surgery.

For hip extensor angular impulse there was no significant changes after surgery (Hortobagyi, et al., 2011), but Vartiainen et al. (2012) found a significant decrease in absolute peak hip extensor moment and a non-significant reduction in absolute peak hip flexor moment. Hip flexor moments had a non-significant increase and hip extensor moment had a non-significant decrease for values normalised to body mass and height (Vartiainen, et al., 2012).

Table 12: Absolute joint moment, angular impulse and accelerometer outcome measures in two surgical weight loss intervention studies. All values Mean ± SD.

Author, Date, Intervention and Follow-up Time	**Joint**	**Sagittal Plane Moments (Nm) PWS/1.2 m/s**	**Sagittal Plane Moments (Nm) 1.5 m/s**	**Frontal Plane Moments (Nm) PWS/1.2 m/s**	**Frontal Plane Moments (Nm) 1.5 m/s**	**Angular Impulse/ Acceleration PWS/1.2 m/s**	**Angular Impulse/ Acceleration 1.5 m/s**
Hortobagyi et al. (2011) Surgery (PWS) T0 – baseline – 1.30 m/s T1 - 7 months – 1.35 m/s T2 - 12 months – 1.45 m/s	Ankle	No data presented	No data presented	No data presented	No data presented	Plantar flexor angular impulse (Nm s) T0 42.2 ± 14.4* T1 30.8 ± 10.2* T2 28.2 ± 9.5*	Plantar flexor angular impulse (Nm s) T0 39.0 ± 13.2* T1 29.8 ± 10.8* T2 28.3 ± 10.6*
	Knee	Peak extensor moment during early stance T0 41.2 ± 25.9 T1 42.0 ± 25.1 T2 46.2 ± 23.2	Peak extensor moment during early stance T0 62.0 ± 36.4 T1 45.9 ± 19.5 T2 51.1 ± 18.7	Internal abductor moment during early stance T0 -47.8 ± 19.9* T1 -36.1 ± 16.8* T2 -37.7 ± 18.7*	Internal abductor moment during early stance T0 -50.7 ± 18.6* T1 -40.3 ± 18.8* T2 -37.0 ± 19.3*	Extensor angular impulse during early stance (Nm s) T0 7.0 ± 5.5 T1 6.5 ± 4.3 T2 6.9 ± 3.8	Extensor angular impulse during early stance (Nm s) T0 8.8 ± 7.0 T1 6.7 ± 4.0 T2 7.6 ± 3.7
	Hip	No data presented	No data presented	No data presented	No data presented	Extensor angular impulse (Nm s) T0 9.8 ± 5.3 T1 8.7 ± 7.5 T2 8.3 ± 3.1	Extensor angular impulse (Nm s) T0 11.3 ± 4.9 T1 9.1 ± 7.3 T2 8.4 ± 3.2
Vartiainen et al. (2012) and Bragge et al. (2014) Surgery (1.2 m/s) 8.8 months	Ankle	No data presented	No data presented	No data presented	No data presented	No data presented	No data presented
	Knee	Peak extensor moment Pre 44 ± 33 Post 33 ± 22	Peak extensor moment Pre 53 ± 37 Post 44 ± 29	Peak abductor moment during early stance Pre 70 ± 22* Post 57 ± 19*	Peak abductor moment during early stance Pre 71 ± 27* Post 62 ± 19*	Initial Peak (v) Acceleration (g) Pre 2.95 ± 1.08* Post 2.11*# Peak to Peak (v)	Initial Peak (v) Acceleration (g) Pre 3.79 ± 0.97* Post 2.93*# Peak to Peak (v)

		Peak flexor moment Pre -50 ± 26* Post -39 ± 19*	Peak flexor moment Pre -61 ± 21* Post -43 ± 20*	Peak abductor moment during late stance Pre 64 ± 22* Post 54 ± 16*	Peak abductor moment during late stance Pre 61 ± 20 Post 53 ± 16	Acceleration (g) Pre 3.71 ± 1.55* Post 2.75*# Initial Peak (xy) Acceleration (g) Pre 2.30 ± 0.91* Post 1.60*# Peak to Peak (xy) Acceleration (g) Pre 2.16 ± 0.88* Post 1.49*#	Acceleration (g) Pre 4.79 ± 1.26* Post 3.73*# Initial Peak (xy) Acceleration (g) Pre 3.05 ± 1.01* Post 2.07*# Peak to Peak (xy) Acceleration (g) Pre 2.89 ± 0.98* Post 1.95*#
	Hip	Peak extensor moment Pre 119 ± 27* Post 89 ± 20*	Peak extensor moment Pre 162 ± 34* Post 123 ± 32*	No data presented	No data presented	No data presented	No data presented
		Peak flexor moment Pre -93 ± 27 Post -86 ± 55	Peak flexor moment Pre -105 ± 28 Post -100 ± 63				

*Significant differences between values (from articles P<0.05), # Calculated values.

Table 13: Normalised joint moment and angular impulse outcome measures in two surgical weight loss intervention studies. All values Mean ± SD.

Author, Date, Intervention and Follow-up time	Joint	Sagittal Plane Moments PWS/1.2 m/s	Sagittal Plane Moments 1.5 m/s	Frontal Plane Moments PWS/1.2 m/s	Frontal Plane Moments 1.5 m/s	Sagittal Plane Angular Impulse PWS	Sagittal Plane Angular Impulse 1.5 m/s
Hortobagyi et al. (2011) Surgery (PWS) T0 – baseline – 1.30 m/s T1 - 7 months – 1.35 m/s T2 - 12 months – 1.45 m/s	Ankle	No data presented	No data presented	No data presented	No data presented	Plantar flexor angular impulse T0 2.0 ± 0.31 Nm/%kg m T1 2.0 ± 0.25 Nm/%kg m T2 2.0 ± 0.22 Nm/%kg m	Plantar flexor angular impulse T0 1.8 ± 0.20 Nm/%kg m T1 1.9 ± 0.23 Nm/%kg m T2 2.0 ± 0.25 Nm/%kg m
	Knee	Peak extensor moment during early stance T0 1.8 ± 0.83 Nm/%kg m* T1 2.8 ± 1.37 Nm/%kg m* T2 3.3 ± 1.08 Nm/%kg m*	Peak extensor moment during early stance T0 2.6 ± 1.09 Nm/%kg m T1 3.1 ± 1.28 Nm/%kg m T2 3.7 ± 1.03 Nm/%kg m	Internal abductor moment during early stance T0 -2.3 ± 0.72 Nm/%kg m T1 -2.2 ± 0.62 Nm/%kg m T2 -2.5 ± 0.71 Nm/%kg m	Internal abductor moment during early stance T0 -2.4 ± 0.66 Nm/%kg m T1 -2.5 ± 0.74 Nm/%kg m T2 -2.5 ± 0.84 Nm/%kg m	Extensor angular impulse during early stance T0 0.31 ± 0.19 Nm/%kg m T1 0.43 ± 0.25 Nm/%kg m T2 0.49 ± 0.19 Nm/%kg m	Extensor angular impulse during early stance T0 0.39 ± 0.23 Nm/%kg m T1 0.44 ± 0.24 Nm/%kg m T2 0.53 ± 0.18 Nm/%kg m
	Hip	No data presented	No data presented	No data presented	No data presented	Extensor angular impulse T0 0.49 ± 0.26 Nm/%kg m T1 0.57 ± 0.43 Nm/%kg m T2 0.61 ± 0.21 Nm/%kg m	Extensor angular impulse T0 0.56 ± 0.24 Nm/%kg m T1 0.60 ± 0.42 Nm/%kg m T2 0.62 ± 0.21 Nm/%kg m

Vartiainen et al. (2012) and Bragge et al. (2014) Surgery (1.2 m/s) 8.8 months	Ankle	No data presented	No data presented	No data presented	No data presented	No data presented	No data presented
	Knee	Peak extensor moment Pre 0.19 ± 0.13 Nm/kg m Post 0.18 ± 0.10 Nm/kg m	Peak extensor moment Pre 0.23 ± 0.15 Nm/kg m Post 0.25 ± 0.15 Nm/kg m	Peak abductor moment during early stance Pre 0.32 ± 0.07 Nm/kg m Post 0.32 ± 0.07 Nm/kg m	Peak abductor moment during early stance Pre 0.32 ± 0.08 Nm/kg m* Post 0.36 ± 0.07 Nm/kg m*	No data presented	No data presented
		Peak flexor moment Pre -0.24 ± 0.14 Nm/kg m Post -0.23 ± 0.12 Nm/kg m	Peak flexor moment Pre -0.29 ± 0.12 Nm/kg m Post -0.26 ± 0.13 Nm/kg m	Peak abductor moment during late stance Pre 0.29 ± 0.09 Nm/kg m Post 0.31 ± 0.07 Nm/kg m	Peak abductor moment during late stance Pre 0.28 ± 0.08 Nm/kg m Post 0.30 ± 0.08 Nm/kg m		
	Hip	Peak extensor moment Pre 0.57 ± 0.15 Nm/kg m Post 0.54 ± 0.10 Nm/kg m	Peak extensor moment Pre 0.76 ± 0.15 Nm/kg m Post 0.75 ± 0.18 Nm/kg m	No data presented	No data presented	No data presented	No data presented
		Peak flexor moment Pre -0.43 ± 0.13 Nm/kg m Post -0.48 ± 0.18 Nm/kg m	Peak flexor moment Pre -0.48 ± 0.10 Nm/kg m Post -0.55 ± 0.21 Nm/kg m				

*Significant differences between values (from articles P<0.05).

4.1 Quality of Articles

Article quality was recorded adopting the critical review form developed by Law et al. (1998) (Appendix A). All included articles had a weight loss intervention and a measure of gait velocity. All studies had ethical approval and had written informed consent from all participants. Due to the intervention aspect of the studies, the participants were recruited through surgery or weight loss programmes. Measurements were taken in a hospital or university laboratory setting for all studies. In terms of participant allocation within the trial three studies were randomised controlled trials, two had participants allocated with sealed envelopes (Castello, et al., 2011; Sarsan, et al., 2006) and one used a block randomised design (Gabriel, et al., 2011).

In studies incorporating two or more intervention groups there were no differences in participant characteristics at baseline for three studies (Castello, et al., 2011; Gabriel, et al., 2011; Sarsan, et al., 2006). Three studies had differences in participant characteristics at baseline (Lemoine, et al., 2007; Stegen, et al., 2011; Vincent, Ben-David, et al., 2012). In the Lemoine et al. (2007) study, the groups were different sizes with premenopausal women (n = 13) being younger than postmenopausal women (n = 27). In the Stegen et al. (2011) study the exercise group was slightly younger, with more females and a higher mean baseline BMI. In the Vincent et al. (2012) study the control group was slightly older, with a lower baseline body mass and BMI.

One study justified its sample size and power within its reported methodology (Castello, et al., 2011). All studies reported results and evaluated findings in terms of statistical significance ($P < 0.5$). Where there was no statistical significances the main reasons cited for the lack of significant effect were attributed to small sample size (Bragge, et al., 2014; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lemoine, et al., 2007; Lyytinen, et al., 2013; Vartiainen, et al., 2012; Vincent, Ben-David, et al., 2012). Where there were drop outs, they were excluded from the results except for De Souza et al. (2009) where the two groups were different sizes (51 vs. 49). The main reason for drop outs were refusal or unable to continue to participate in the intervention or unable to contact for follow-up measurements.

There may have been biases operating where participants were encouraged to participate or increase physical activity but no formal exercise programme was in place (Josbeno, et al., 2010; Plewa, et al., 2007; Vincent, Ben-David, et al., 2012) or where diet was not controlled (Sarsan, et al., 2006). This could affect results by improving physical function and gait outcome measures and affecting weight loss. In one study participants self-selected to an exercise intervention group after surgery (Stegen, et al., 2011). The participants that chose to be in the exercise group may be more likely to participate in exercise after surgery than participants that chose to be in the control group.

Besides a small sample size, other limitations of the included studies were the lack of non-weight loss control group (Hortobagyi, et al., 2011; Vargas, et al., 2013), short intervention duration (Lemoine, et al., 2007) and funding being stopped 12 months before the end of the intervention period (Gabriel, et al., 2011). Some studies used mainly female participants (Bragge, et al., 2014; Lyytinen, et al., 2013; Sarsan, et al., 2006; Vartiainen, et al., 2012) and some studies had participants that had a similar background and from a limited geographic area (Gabriel, et al., 2011; Tompkins, et al., 2008) so results would not be representative of the entire population. Limitations with outcome measures included marker placement accuracy (Hortobagyi, et al., 2011; Vartiainen, et al., 2012), not using PWS for gait analysis (Bragge, et al., 2014; Vartiainen, et al., 2012), no measurements of kinematic and kinetic outcome measures (Plewa, et al., 2007). For the 6MWT the age, gender, height and body mass characteristics of the participants may not have been factored into the results (De Souza, et al., 2009) and there may not have been enough participants to give normative data of the included population (Tompkins, et al., 2008). It was difficult to exclude all comorbid conditions (Maniscalco, et al., 2006), and there was a lack of focus addressing the barriers to physical activity (Josbeno, et al., 2010).

The articles that were deemed the most relevant in terms of comprehensive and detailed kinematic and kinetic biomechanical data were the studies by Hortobagyi et al. (2011), Vartiainen et al. (2012) and Bragge et al. (2014). These studies used surgery interventions which gave significant reduction in body mass and allowed for comparisons between pre and post intervention.

5. Discussion

In this chapter the outcome measurements from the published studies included in the systematic review will be considered with respect to the effect weight loss interventions had on the biomechanical parameters of gait, the limitations of the studies and areas where there is the need for further research.

5.1 Overview of Results

An outcome measurement common to all studies included in the systematic review was gait velocity. This was either directly measured or calculated through a functional walking test, and improved after a reduction in body mass due to diet, exercise and surgery interventions. Despite a reduction in body mass after the interventions, none of the participants reached the normal range BMI and at best were classed as overweight. Twelve of the 15 studies used surgery as a weight loss intervention, and as bariatric surgery is a last resort option, in many cases the participants would tend to be extremely obese. Even after losing 20 – 75 kg after surgery with participants having initial BMI over 40 kg/m^2 the post-surgery BMI was still between 28 – 40 kg/m^2 (Bragge, et al., 2014; Castello, et al., 2011; De Souza, et al., 2009; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, et al., 2013; Vartiainen, et al., 2012; Vincent, Ben-David, et al., 2012).

Temporal-spatial parameters of gait outcome measure data was presented from four studies. However as three of the four studies used surgery as the weight loss intervention there is very little temporal-spatial parameter data for weight loss through diet and exercise interventions. The current research on 3D gait kinematics and kinetics after weight loss interventions came from two studies. As a result there was little overlap in angular and moment measurements which made it difficult to compare the data, for example Vartiainen et al. (2012) did not present ankle data and Hortobagyi et al. (2011) presented mean flexion angular displacement and angular impulse (Tables 10, 12, 13). There was also a difference between the gait velocities at which the measurements were taken; Hortobagyi et al. (2011) used the participants PWS and Vartiainen et al. (2012) set the velocity at 1.2 m/s.

5.2 Weight Loss

Obese individuals lost body mass after the interventions. Due to the immediate nature of bariatric surgery, even with higher baseline body mass, surgery interventions produced the greatest amount of body mass lost with 11 of the 12 surgery interventions having a significant reduction in body mass (Bragge, et al., 2014; Castello, et al., 2011; De Souza, et al., 2009; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, et al., 2013; Vartiainen, et al., 2012). With the diet and/or exercise interventions, the amount of total body mass lost was lower than with the surgery interventions, although four of the five diet and/or exercise interventions gave a significant reduction in body mass (Evers Larsson & Mattsson, 2003; Lemoine, et al., 2007; Plewa, et al., 2007; Sarsan, et al., 2006).

Besides bariatric surgery being the principle intervention for massive reduction in body mass in severely obese individuals, reasons for diet and exercise interventions having smaller body mass loss could be due to intervention duration, type of intervention and initial body mass of participants. The three diet and exercise combined interventions were all of different durations (Gabriel, et al., 2011; Lemoine, et al., 2007; Plewa, et al., 2007). The 3-week intervention had an average reduction in body mass of 2 kg but participants had to exercise for 70 minutes, six times a week (Lemoine, et al., 2007). Even though participants on the 12-week intervention lost on average 7 kg, they consumed less energy and were encouraged to exercise for 30 – 60 minutes 3 – 5 times a week (Plewa, et al., 2007). If the 3-week intervention was extended to 12-weeks, assuming the average body mass loss is the same for every three weeks the total body mass lost would be a similar amount. Longer duration studies are required to see if weight loss continues, however current research has not found the optimal intervention duration to reach normal BMI. The 48-month intervention focussed on changing the lifestyle of participants by teaching them to eat healthily and participate in physical activity (Gabriel, et al., 2011). These lifestyle intervention participants lost an average of 3 kg which was not significant, however their baseline body mass was approximately 10 kg less than participants in the Lemoine et al. (2007) and Plewa et al. (2007) studies.

The exercise interventions used aerobic exercise as it can be administered easily through walking and as well as weight loss it can also improve body composition, physical performance and cardiovascular risk factors (Maffiuletti, et al., 2005). Two studies included in the systematic review which used a 3-month exercise programme after surgery intervention showed differing effects on increasing the amount of body mass lost at 4-month follow-up which could be due to differences in the exercise programmes. Castello et al. (2011) found no difference between the surgery only and surgery and exercise groups using aerobic exercise for one hour, three times a week. Whereas Stegen et al. (2011) found significantly greater body mass loss in the surgery only group than the surgery and exercise group. However the surgery and exercise group had higher initial body mass which could influence the results of the exercise programme which included aerobic and resistance exercise. Sarsan et al. (2006) compared aerobic and resistance exercise programmes. On average participants lost an average of 1 kg more body mass after aerobic exercise than resistance exercise, however resistance exercise has been shown to be more effective in maintaining and improving muscle strength and fat free mass which is more useful for functional activities and gait (Strasser & Schobersberger, 2010). The addition of resistance training can reduce the amount of body mass lost through exercise (Weiss, et al., 2007) but improve muscle strength (Sarsan, et al., 2006; Stegen, et al., 2011; Strasser & Schobersberger, 2010), thus offering differing benefits to health and wellbeing.

Where there were multiple follow-ups (6 and 12 months) the body mass continued to reduce significantly from baseline measurements after surgery only interventions (Hortobagyi, et al., 2011; Tompkins, et al., 2008). However, after diet only intervention in Evers Larsson's (2003) study, at the second follow-up (64 weeks) obese participants had regained some body mass. This may be due to the increase in energy consumption after the initial 12-week diet intervention (Evers Larsson & Mattsson, 2003) or issues with adherence to the diet after the initial intervention period (Asher, et al., 2013). Or obese participants undergoing surgery interventions having higher initial body mass than obese individuals participating in diet and exercise interventions, this is due to individuals having to be morbidly obese (BMI > 40 kg/m^2 or BMI > 35 kg/m^2 with at least two comorbidities) before surgery is considered (Asher, et al., 2013; Silver, et al., 2006). This suggests the total body mass lost may also depend on the initial body mass of obese individuals as well as the weight loss method and duration of intervention (Santarpia, Contaldo, & Pasanisi, 2013).

With a reduction in body mass it was expected that BMI classification of participants would reduce. However, even with the large reductions in body mass that occurred the participants in all studies included in the review were still classed as overweight or obese from the BMI.

There were no interventions that ended with participants in the normal BMI range (18 – 25 kg/m^2) within the timeframe of the study. BMI after weight loss stabilisation has been linked to age, body mass at 21 years old, pre-surgery BMI and time spent participating in physical activity (Silver, et al., 2006). Silver et al. (2006) reported that surgery patients were still trying to lose body mass two years after bariatric surgery but may be limited by metabolic adaptation, suggesting that patients are unable to reduce their body mass to less than their body mass was at age 21. Obese individuals are more likely to participate in more physical activity after all types of weight loss interventions for weight maintenance and health benefits (Evers Larsson & Mattsson, 2003; Pronk & Wing, 1994; Silver, et al., 2006).

5.3 Effect of Weight Loss on Gait

After weight loss interventions significant improvements to the temporal-spatial parameters were increased velocity, swing time (Hortobagyi, et al., 2011; Plewa, et al., 2007; Vincent, Ben-David, et al., 2012), step length (Vincent, Ben-David, et al., 2012), stride length (Hortobagyi, et al., 2011; Plewa, et al., 2007) and cadence; and reduced double support, stance time, cycle time (Plewa, et al., 2007) and stance width (Vartiainen, et al., 2012). In a number of these studies the cadence and stride length (Hortobagyi, et al., 2011; Plewa, et al., 2007; Vartiainen, et al., 2012; Vincent, Ben-David, et al., 2012), were within the normative temporal-spatial parameters for adults (Kirtley, 2006). Although most of the subjects were still classed as overweight, they were closer in mass to a healthy weight individual, and similarities in temporal-spatial parameters such as gait velocity, cadence and stride length have been found between overweight and healthy normal weight individuals (Błaszczyk, et al., 2011; Sheehan & Gormley, 2013).

After weight loss interventions the stance duration was still slightly increased and the swing duration slightly reduced compared to healthy normal weight individuals (Hortobagyi, et al., 2011; Plewa, et al., 2007; Vartiainen, et al., 2012; Vincent, Ben-David, et al., 2012), due to participants still being overweight and requiring the additional stance time for stability during gait (Błaszczyk, et al., 2011; Browning & Kram, 2007; Lai, et al., 2008; Malatesta, et al., 2009; Plewa, et al., 2007; Sheehan & Gormley, 2013; Spyropoulos, et al., 1991; Vismara, et al., 2007). This was also seen in a study with overweight individuals having similar increased double support time and stance phase duration to obese individuals in comparison to normal healthy weight individuals (Sheehan & Gormley, 2013). Spyropoulos et al (1991) suggested the longer stance duration for obese individuals was to generate adequate push off force to overcome inertia of carrying additional mass.

Although the reduced stance width and toe out angle after surgery were not significantly different to the control group, there are still links to participants having a more stable base of support during gait after weight loss (Vincent, Ben-David, et al., 2012). A reduced thigh circumference (Lyytinen, et al., 2013) which would reduce the friction between the legs during gait (Browning, et al., 2009; Malatesta, et al., 2009; Spyropoulos, et al., 1991; Vismara, et al., 2007; Westlake, et al., 2013; Wu, et al., 2012) could be a factor in reducing stance width.

Gait velocity improved after weight loss interventions in all studies included in the systematic review. There was no difference for gait velocity values whether it was measured directly or calculated through functional walking tests. The baseline gait velocity was between 1.06 – 1.67 m/s. The fastest baseline gait velocity was measured using 6MWT by Lemoine et al. (2007); however the value of total distance walked was extracted from graphical data as opposed to reported values therefore the calculated gait velocity might not be accurate. The values for 6MWT distance walked by participants in the Lyytinen, et al. (2013) study were also taken from a graph.

Post intervention gait velocities improved to 1.12 – 1.79 m/s, becoming closer to the 1.33 – 1.64 m/s reported for healthy adults (Freedman Silvernail, et al., 2013; Kirtley, 2006; Malatesta, et al., 2009; Spyropoulos, et al., 1991). After surgery interventions there was a greater improvement (mean 0.22 m/s, range 0.04 – 0.42 m/s, improved to 1.23 – 1.74 m/s) in gait velocity than after diet and exercise (mean 0.13 m/s, range 0.2 – 0.43 m/s, improved to 1.12 – 1.79 m/s) interventions which could be related to the larger reduction in body mass.

Improvements in physical function are seen through the improvements in distance walked in the 6MWT (Castello, et al., 2011; De Souza, et al., 2009; Gabriel, et al., 2011; Josbeno, et al., 2010; Lemoine, et al., 2007; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Sarsan, et al., 2006; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, et al., 2013), which are due to the reduction in excess body mass and BMI (Beriault, et al., 2009; Dourado & McBurnie, 2012; Evers Larsson & Reynisdottir, 2008; Gontijo, et al., 2011; Iwama, et al., 2009). The highest post intervention gait velocities were also from the two studies where there was the most improvement in gait velocity calculated from distance walked in 6MWT (Maniscalco, et al., 2006; Sarsan, et al., 2006). Maniscalco et al. (2006) had one of the longest post-surgery follow-up times at 12 months which may be a reason for the large improvement in gait velocity (0.42 m/s; 1.32 to 1.74 m/s) and distance walked (150.6 m; 475.7 to 626.3 m). In comparison the two other studies with a 12-month follow-up time had gait velocity improvements of only 0.15 m/s (De Souza, et al., 2009; Hortobagyi, et al.,

2011) but the participants were over 40 years old, an average of 6 years older which could affect gait velocity (Boyer, Andriacchi, & Beaupre, 2012; Huang et al., 1998). Whereas the large improvement in gait velocity (0.43 m/s; 1.36 to 1.79 m/s) and distance walked (148.2 m; 490.5 ± 75.4 to 644 ± 104.22 m) from the participants in the Sarsan et al. (2006) study was from 12-weeks of aerobic training which suggests that aerobic exercise improves the aerobic capacity of obese individuals (De Souza, Faintuch, & Sant'anna, 2010; Ghroubi, et al., 2009; Weiss, et al., 2007). In comparison, a 12-week diet intervention had post intervention gait velocity of 1.27 m/s (0.08 m/s improvement) as the main intervention focus was on diet with limited encouragement for aerobic exercise (Evers Larsson & Mattsson, 2003; Plewa, et al., 2007). When tested three months after surgery the improvements in gait velocity were lower (0.4 – 0.25 m/s) as no exercise programme was included as part of the weight loss intervention (Castello, et al., 2011; Josbeno, et al., 2010; Stegen, et al., 2011; Tompkins, et al., 2008; Vargas, et al., 2013; Vincent, Ben-David, et al., 2012). Where an additional three month exercise programme was used after surgery (Castello, et al., 2011; Stegen, et al., 2011) the improvements in gait velocity were 0.14 m/s, but the post intervention body mass of the participants was still higher than the baseline body mass of aerobic exercise group participants in the Sarsan et al. (2006) study who had the highest post intervention velocity recorded, which suggests body mass needs to be lost initially before improvements in aerobic capacity are seen.

As weight force is related to mass and acceleration due to gravity it would be expected that obese individuals have increased GRF. With the reduction in body mass the absolute GRF reduced significantly for vertical, anterior-posterior (1st vertical peak reduced 27.6% and 1st AP peak reduced 23.8% with 27.2% weight loss) (Hortobagyi, et al., 2011) (1st vertical peak reduced 20.8% and 1st AP peak reduced 19.5% with 21.5% weight loss (Bragge, et al., 2014)) and medio-lateral (Bragge, et al., 2014) directions and there was an associated reduction in the rate of the loading response (Bragge, et al., 2014; Hortobagyi, et al., 2011). When normalised to body mass, there is little difference between the GRF for obese individuals and normal healthy weight individuals, this suggests that forces acting on obese individuals are proportional to body mass (Bragge, et al., 2014; Browning & Kram, 2007; Hortobagyi, et al., 2011; Lai, et al., 2008). This was shown with no significant changes in normalised AP GRF values and loading response for obese individuals after surgery compared to the age matched healthy weight comparison group at the fast gait velocity (Hortobagyi, et al., 2011). However, there were still significant differences compared to healthy weight individuals in absolute and normalised vertical GRF, absolute breaking force and normalised loading response post-surgery which suggests that the ~20 kg of additional body mass that the obese individuals were carrying is significant (Hortobagyi, et al., 2011).

At the faster gait velocity the absolute GRF values were slightly greater as more force is required to be generated for propulsion (Bragge, et al., 2014; Browning & Kram, 2007; Hortobagyi, et al., 2011). Although when PWS increased after surgery there was still a significant reduction in absolute GRF after surgery which would be related to the weight loss (Hortobagyi, et al., 2011). However the normalised peak vertical and AP GRF increased after surgery due to the increase in PWS (Hortobagyi, et al., 2011) as more force generation would be required during TO (Browning & Kram, 2007). This was shown by Lai et al. (2008), where the 2^{nd} vertical peak GRF was lower in obese individuals especially with a slower walking velocity which would be expected as lower force generation is required during TO at slower walking velocities.

After surgery the decrease in ML GRF was significantly greater than mean weight loss, due to a reduction in step width (Bragge, et al., 2014). Browning and Kram (2007) also showed an increase in ML peak was not proportional to the increase in weight, so attributed it to increased step width.

The two studies (Hortobagyi, et al., 2011; Vartiainen, et al., 2012) that measured joint angular displacement and moment data were difficult to directly compare as the outcome measures were taken from different points in the gait cycle. For example Hortobagyi et al. (2011) reported mean angular displacements and Vartiainen et al. (2012) reported values at IC and TO. Only the faster gait velocity (1.5 m/s) can be compared between the two studies (Hortobagyi, et al., 2011; Vartiainen, et al., 2012) as the slower gait velocity (1.2 m/s) set by Vartiainen et al. (2012) was slower than the PWS for participants in the Hortobagyi et al (2011) study. In addition the PWS increased in velocity with each follow-up (Hortobagyi, et al., 2011) which has an impact on kinematic and kinetic measures (Browning & Kram, 2007; DeVita & Hortobagyi, 2003; Ko, et al., 2010; Lai, et al., 2008; Samson, et al., 2001).

Post-surgery intervention there was a significant reduction in mean dorsi flexion during stance phase from the pre surgery measurements at both velocities (PWS and 1.5 m/s) (Hortobagyi, et al., 2011). This may be due to the increased PWS as with an increase in velocity there is reduced dorsi flexion in late stance phase (Kirtley, 2006) and increased ankle function (Hortobagyi, et al., 2011). There were no significant differences in angular displacement after surgery between obese individuals and the age matched healthy weight comparison group, even with the obese individuals being approximately 20 kg heavier (Hortobagyi, et al., 2011), this shows there is little difference in gait kinematics between overweight and normal healthy weight individuals. Where ROM during gait for overweight individuals was similar to gait kinematics of healthy weight individuals this could be due to gait not requiring the use of the full joint ROM (Browning & Kram, 2007; Freedman Silvernail, et al., 2013; Lai, et al., 2008; Vismara, et al., 2007).

There were contrasting findings for knee angular displacement during early stance phase between the two studies after surgery for the slower walking velocities (PWS and 1.2 m/s). Hortobagyi et al. (2011) showed an increase in peak flexion during early stance phase at 12 months whereas Vartiainen et al. (2012) showed a decrease in peak flexion at 8.8 months. After weight loss, knee flexion would be expected to reduce as a reduced body mass requires lower shock absorption during loading response. This was shown through reduced axial and shear knee initial peak accelerations after surgery (Bragge, et al., 2014). At the faster walking velocity, Hortobagyi et al. (2011) showed 1° reduction in knee angle during early stance phase at 7 months and Vartiainen et al. (2012) showed the same values at baseline and post-surgery which suggest knee flexion at IC is used for additional shock absorption due to the increased forces generated by the faster velocity and to produce greater propulsive forces at TO (Hortobagyi, et al., 2011; Vartiainen, et al., 2012). Hortobagyi et al. (2011) found only a 0.1° difference at 12 months post-surgery for knee angle during early stance phase between PWS and the faster gait velocity (1.5m/s) which suggests the increase in knee flexion during early stance phase is due to the increase in PWS (Da Silva-Hamu, et al., 2013; DeVita & Hortobagyi, 2003; Kirtley, 2006). An increase in knee flexion may be due to less fat tissue inhibiting movement at the joints, thus allowing a greater ROM. This was shown by Lyytinen et al. (2013) where knee flexion increased significantly after surgery but changes in knee extension were non-significant.

For hip angular displacement the outcome measurements were not comparable between the two studies. At IC Vartiainen et al. (2012) found reduced hip flexion, which is indicative of obese participants walking with a more erect posture as shown by De Vita and Hortobagyi (2003). During stance phase Hortobagyi et al. (2011) showed an increase in mean hip flexion and an increase in hip ROM during swing phase. Increased hip ROM may be due to reduced excess fat mass especially at the abdomen which would allow for greater movement at the hip and pelvis (Blake, et al., 2000; Ling, et al., 2009) and allow for increased leg swing to produce longer strides (Hortobagyi, et al., 2011).

Hortobagyi et al. (2011) found a significant reduction in absolute plantar flexor angular impulse after surgery but no significant difference when normalised (to % body mass and height). The reduction in absolute plantar flexor angular impulse is due to obese individuals using greater ankle moment for stabilisation and to reduce the muscle moment at the knee during walking (Da Silva-Hamu, et al., 2013; DeVita & Hortobagyi, 2003). With the weight loss after surgery the reduction in absolute plantar flexor angular impulse suggests that the gait function has adapted to reduce the role of the ankle during gait as the absolute knee extensor angular impulse changes very little but the normalised knee extensor angular impulse increased which would imply the knee is being utilised rather than relying on ankle function (Hortobagyi, et al., 2011). There were significant differences in normalised hip extensor angular impulse between obese individuals compared to age matched healthy weight individuals, however there were no significant changes in normalised hip extensor angular impulse for obese individuals after surgery (Hortobagyi, et al., 2011).

Absolute peak knee flexor and extensor moments reduced after surgery but peak knee extensor moments increased when normalised (Hortobagyi, et al., 2011; Vartiainen, et al., 2012). Increased external knee adduction moments have been linked to osteoarthritis in obese individuals (Browning & Kram, 2007; Freedman Silvernail, et al., 2013; Segal, et al., 2009; Sheehan & Gormley, 2013). With suggestions that obese individuals adapt their gait to alter the forces acting on the knee joints and reduce pain (Browning & Kram, 2007; DeVita & Hortobagyi, 2003). In Hortobagyi et al.’s (2011) study when comparing obese individuals to the age matched healthy weight comparison group, there were significant differences in absolute knee extensor angular impulse and knee peak extensor moment in early stance phase. The differences in absolute joint moment and angular impulse could be due to the additional body mass the obese individuals are carrying even after surgery (Hortobagyi, et al., 2011). The reduction in absolute knee moments is expected with the reduction in body mass after surgery and as the changes in normalised moments is non-significant the reduction in absolute moment would be proportional to body mass lost (Vartiainen, et al., 2012). It has previously been shown that when normalised to body mass, there is little difference between the moments for obese individuals and normal healthy weight individuals suggesting that joint moments during gait are proportional to body mass (Browning & Kram, 2007; Lai, et al., 2008; Sheehan & Gormley, 2013).

Frontal plane absolute abductor moments during early stance phase reduced after surgery which would be expected after weight loss (Hortobagyi, et al., 2011; Vartiainen, et al., 2012). At the faster gait velocity, the baseline abductor moment values were higher but improved after surgery to become closer to the slower velocity baseline values. The reduction in abductor moments could reduce the risk of developing osteoarthritis (Freedman Silvernail, et al., 2013). However, the increase in abductor moment when normalised could be due to weight loss not having an effect on individuals with knee osteoarthritis (Letts et al., 2007). Suggesting that the obese individuals still have to alter the direction of the force vector relative to joint position to reduce total load at the knee joint possibly through externally rotating the leg or having a valgus knee alignment (Browning & Kram, 2007; DeVita & Hortobagyi, 2003).

There was a significant decrease in absolute peak hip extensor moment and a non-significant reduction in absolute peak hip flexor moment after surgery intervention (Vartiainen, et al., 2012). When normalised to body mass and height there was an increase in hip flexor moments and reduction in hip extensor moments (Vartiainen, et al., 2012). The reduction in hip extensor moments would be expected with the reduction in body mass after surgery and as the changes in normalised moments is non-significant the reduction in absolute moment would be proportional to body mass lost (Vartiainen, et al., 2012).

5.4 Limitations

Data collection for 3D kinematic and kinetic gait is more difficult when using obese participants. This may be a reason for the lack of research in the area of gait in obese individuals as it is difficult to palpate for specific bony landmarks required for marker placement (Borhani, et al., 2013; Lerner, et al., 2014; Menegoni, Vismara, et al., 2009; M. Smith, et al., 2013). There may also be an issue with obese individuals being more sensitive and self-conscious, as to obtain the best results from 3D gait analysis participants are required to wear tight fitting clothing to reduce marker movement (Atlantis, Barnes, & Ball, 2007; Mazzocchi, et al., 2012; Sallinen, et al., 2009; Wee, et al., 2013). Although there will be a degree of marker movement due to skin artefact, in obese participants it may cause more of an effect as there is more subcutaneous fat mass that can cause this (Cereatti, Donati, Camomilla, Margheritini, & Cappozzo, 2009; Lerner, et al., 2014; Wu, et al., 2012). The limitations of data collection on obese participants could affect the accuracy of the kinematic and kinetic gait data reported and included in the systematic review.

Modified Helen Hayes marker sets were used in the two studies that measured 3D kinematic outcome measures (Hortobagyi, et al., 2011; Vartiainen, et al., 2012), in addition Hortobagyi et al. (2011) also calculated hip joint centres using a measured radius, 25% of the distance between the right and left greater trochanters at the hip joint centre depth and the greater trochanter marker for vertical and anterior-posterior position. With body mass loss Hortobagyi et al. (2011) found marker placement changed by 1 – 2 cm due to reduction in soft tissue. Recent progress has been made in using functional joint centres which will make it easier to perform 3D gait analysis on obese participants as markers would not be required to locate joint centres (Begon, et al., 2007; Camomilla, et al., 2006; Corazza, et al., 2007; Ehrig, Taylor, Duda, & Heller, 2006; Krauss, et al., 2012; Leardini, et al., 1999). Use of an obesity specific marker set would also improve the accuracy of 3D gait analysis (Lerner, et al., 2014). With body mass loss it is likely that body segment parameters will change which will affect calculations for kinematic and kinetic joint data so MRI or DEXA scanners can be used to measure body segments more accurately (Chambers, et al., 2010; Matrangola, et al., 2008). However, with body mass loss it may make it easier to palpate for bony landmarks with reduced subcutaneous fat mass.

When performing gait analysis there is the problem of whether to have participants walk at their PWS or to use set walking velocities. If participants are walking at their PWS, it is more likely that they would walk naturally rather than be restricted by a set velocity. However, it is easier to compare participants when they all walk at the same velocity especially after a weight loss intervention when PWS increases. In the three studies where the same participants were used, the 6MWT showed an increase in walking velocity (Lyytinen, et al., 2013) but the gait analysis used preselected velocities (Bragge, et al., 2014; Vartiainen, et al., 2012) so participants were not walking at their PWS as the calculated velocity from the 6MWT was 1.39 m/s which is in between the two set velocities of 1.2 and 1.5 m/s. After surgery the walking velocity from the 6MWT increased to 1.56 m/s which was nearer the faster gait velocity. There were also differences when using PWS as the gait velocity increased after surgery from 1.30 m/s to 1.35 m/s at 7 months and 1.45 m/s at 12 months (Hortobagyi, et al., 2011).

Although there were a number of studies using obese participants undergoing a bariatric surgery intervention the numbers of participants in the studies were low (Castello, et al., 2011; Hortobagyi, et al., 2011; Josbeno, et al., 2010; Lyytinen, et al., 2013; Maniscalco, et al., 2006; Stegen, et al., 2011; Vartiainen, et al., 2012). This may have an effect on the significance of results obtained.

There were more studies with female participants; this may be due to some of researchers focusing only on female subjects (Castello, et al., 2011; Evers Larsson & Mattsson, 2003; Gabriel, et al., 2011; Lemoine, et al., 2007; Maniscalco, et al., 2006; Plewa, et al., 2007; Sarsan, et al., 2006). However, even where researchers used both males and females there were more female participants included. This may be due to females being more self-conscious of being overweight or obese and wanting to lose body mass (Atlantis, et al., 2007; Ball, Crawford, & Owen, 2000).

Obese individuals that are undergoing a surgery intervention may be easier for researchers to recruit through hospitals than obese individuals to participate in diet and exercise interventions. There is also the problem of participants dropping out from interventions and studies. It may be more difficult for obese participants to adhere to diet and exercise interventions especially if they are not seeing a difference in their body mass (Pronk & Wing, 1994).

5.5 Further Research

As the population continues to become obese there is a need for further research in the area of obesity and gait, especially after weight loss interventions. There have been a greater number of studies using bariatric surgery interventions as it is easy to take measurements pre and post-surgery with a large change in body mass in a short period of time. However further research on diet and exercise interventions with longer duration interventions would be more beneficial to obese individuals.

With diet and exercise interventions there is initial weight loss but after a year participants are likely to regain body mass resulting in smaller differences in body mass lost from baseline to one year follow-up (Evers Larsson & Mattsson, 2003; W. C. Miller, et al., 1997). This may be a reason why participants have not lost enough body mass to be classified as normal weight. However with multiple follow-ups after surgery there is additional body mass lost at each follow-up (Hortobagyi, et al., 2011; Tompkins, et al., 2008). Longer follow-up times may be required for participants to reach the normal weight classification.

Further research using kinematic and kinetic outcome measure for gait in obese individuals and after weight loss is required to determine how much of an effect obesity had on the musculoskeletal system and whether or not it is possible to return to a healthy weight and reduce the risk of musculoskeletal disorders and other health comorbidities. As yet there have not been any studies where obese participants lose enough body mass from an intervention to be transformed into the normal BMI range.

6. Conclusion

From the published research, weight loss interventions have significant benefits for the improvement of gait temporal-spatial parameters. The limited 3D gait analysis available suggests that there is an improvement in gait function following weight loss and therefore the potential to reduce the risk of developing further musculoskeletal disorders. This is evidence by reduced GRF, reduced moments at the ankle, knee and hip joints, reduced ankle dorsi flexion and knee flexion during stance phase and increased hip ROM during swing phase.

However there has been limited research on gait kinematics and kinetics after weight loss. As a result, there was limited overlap in measurement outcomes in the two studies undertaking 3D gait analysis following weight loss surgery which made it difficult to compare the results of the outcome measures. The conclusions drawn from these two studies is tentative as further research is required to confirm these changes are always apparent after weight loss.

Participants in all studies lost body mass after the dietary restriction, exercise and surgery interventions. Baseline mean BMI for participants in all studies was categorised as obese. Despite the large reduction in body mass, participants in all studies did not reach normal BMI after weight loss interventions. Gait velocity improved after weight loss from the separate dietary restriction, exercise training and surgery interventions. Cadence and stride length improved to within normative temporal-spatial parameters, where reported.

The amount of body mass lost and improvements to gait velocity were dependent on type of weight loss intervention and duration of intervention. Further research is required on how weight loss affects the walking gait of obese individuals, especially after dietary and exercise interventions. Also, to find the optimal duration for weight loss interventions for obese participants to be classed as normal BMI after weight loss.

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Appendix A

	Introduction - Background and Objectives				
Author and Date	**Was the study purpose stated clearly?**	**Outline purpose of study**	**How does study apply to my research question?**	**Was relevant background literature reviewed?**	**Describe the justification of the need for this study**
Castello et al. (2011)	Yes	evaluate whether a 12 week aerobic exercise training programme can modify heart rate variability and functional capacity in severely obese women 4 months after gastric bypass surgery	weight loss through bariatric surgery, functional capacity through 6MWT	yes	no previous study that has investigated the effects of a physical training programme after gastric bypass surgery on heart rate variability in morbidly obese patients
De Souza et al. (2009)	Yes	study the functional capacity of a severely obese population before and after bariatric surgery	weight loss through bariatric surgery, functional capacity through 6MWT	yes	6MWT can be used on severely obese patients who could not tolerate other functional capacity tests
Evers Larsson et al. (2003)	Yes	investigate the effects of weight reduction by dieting on walking speed, relative oxygen cost, exhaustion and pain in obese women during level walking	weight loss through dieting, level walking speed	yes	exercise tolerance decreases as BMI increases, diet used for weight loss rather than exercising

Gabriel et al. (2011)	Yes	determine whether changes in leisure time physical activity and body composition reflect concomitant changes in 400m walk time	weight loss through diet and physical activity changes, physical function through 400m walk	yes	unknown whether 400m walk can be used as a marker of physical function
Hortobagyi et al. (2011)	Yes	quantify the effects of metabolic surgery induced weight loss on gait biomechanics of obese but otherwise healthy individuals and compare their gait after weight loss to the gait of lean age and gender matched comparison group	weight loss through bariatric surgery, gait biomechanics	yes	measure adaptation of joint moments after weight loss
Josbeno et al. (2010)	Yes	investigate the changes in physical activity, physical function, health related quality of life and psychosocial correlates of physical activity before and after bariatric surgery	weight loss through bariatric surgery, physical function through 6MWT	yes	limited studies have investigated the effect of bariatric surgery on objective measures of physical function - specifically whether an increase in physical function is associated with an increase in physical activity after surgery

Lemoine et al. (2007)	Yes	examine the impact of a 3 week weight reducing programme on body composition, physical condition, health related quality of life and eating behaviours of sedentary obese women, according to menopause status and menopause duration	weight loss through diet and physical activity, physical condition through 6MWT	yes	no previous study has examined the impact of a short term programme including diet and regular aerobic exercise on pre and post-menopausal women studied concomitantly
Maniscalco et al. (2006)	Yes	assess the magnitude of differences in walking capacity and perceived symptoms in obese subjects after weight loss induced by bariatric surgery	weight loss through bariatric surgery, functional capacity through 6MWT	Yes	the influence of the level of physical activity on walking ability in obese subjects after bariatric surgery has not been investigated
Plewa et al. (2007)	Yes	investigate whether a 3 month weight reduction treatment influences gait in obese women	weight loss through diet, gait parameters	Yes	limited studies focusing on the influence of overweight or obesity on locomotion function, no studies on the effects of weight loss treatment on gait characteristics
Sarsan et al. (2006)	Yes	compare the effects of aerobic and resistance exercise on weight, muscle strength, cardiovascular fitness, blood pressure and mood in obese women who were	weight loss through exercise, functional capacity through 6MWT	Yes	no other studies investigating effects of aerobic and resistance exercise in obese women who were not under energy restricted diet

		not on an energy restricted diet			
Stegen et al. (2011)	Yes	investigate the effect of gastric bypass surgery on physical fitness and to determine if an exercise programme in the first 4 months is beneficial	weight loss through bariatric surgery and exercise, functional capacity through 6MWT	Yes	bariatric surgery is currently most efficacious and long term treatment for clinically severe obese, but undetermined whether poor physical fitness, an important characteristic of these patients, improves as well
Tompkins et al. (2008)	yes	whether 6MWT distances varied for patients before and after surgery, examine the relationship between functional walking distances and patients perceptions of health related quality of life before and after surgery	weight loss through bariatric surgery, functional capacity through 6MWT	yes	early physical functional changes after gastric bypass surgery are unclear and relationships between these changes and health related quality of life has not been reported
Vargas et al. (2013)	yes	evaluate functional capacity of morbidly obese patients before and after (3 months) bariatric surgery	weight loss through bariatric surgery, functional capacity through 6MWT	yes	currently no studies that demonstrate improvement in functioning and degree of motor and cognitive dependence of obese individuals after bariatric surgery
Vartiainen et al. (2012)	yes	examine effects of bariatric surgery induced weight loss on the gait of obese subjects	weight loss through bariatric surgery, gait biomechanics	yes	only one other study evaluating effects of weight loss on the biomechanics of walking

					in obese
Lyytinen et al. (2013)	yes	assess the changes in physical function and the properties of the quadriceps femoris muscle in excessively obese subjects after bariatric surgery and subsequent weight loss	weight loss through bariatric surgery, physical function through 6MWT	Yes	little is known about the effects of weight loss after bariatric surgery on fat mass and the muscle structure of the lower extremities
Bragge et al. (2014)	yes	examine how impulsive loading would change walking in severely obese subjects after surgery	weight loss through bariatric surgery, GRF	Yes	currently few studies evaluating role of bariatric surgery in joint loading and changes in gait
Vincent et al. (2012)	yes	determine whether rapid changes in walking speed, gait, perceived physical function and quality of life occur after bariatric surgery	weight loss through bariatric surgery, gait biomechanics	Yes	conventional diet an physical activity interventions for long term treatment of morbid obesity have slow rate of change in body composition, pain and function

						Study Design and Participants					
Author and Date	**Study design**	**Was the design appropriate for the study**	**Specify any biases that may have been operatin**	**Sample - number**	**Was the sample described in detail?**	**How was sample identified? Was it a representative sample?**	**Setting and location where data was collected**	**Similarities and differences between groups (if more than one)**	**Was sample size justified?**	**Was power discussed?**	**Describe ethics procedures. Was informed consent obtained?**

		question?	**g and the direction of their influence on the results**								
Castello et al. (2011)	randomised controlled trial - sequentially numbered, sealed, opaque envelopes	yes		32	yes - gender, age, BMI	from gastroenterologist physician	cardiopulmonary physiotherapy laboratory at Federal University of Sao Carlos	no differences at baseline between groups	yes, 7 in each group to demonstrate mean difference, anticipating 30% dropout, 32 patients were randomised into 2 groups	yes, 80% power	ethics committee for human research of institutions approval
De Souza et al. (2009)	before and after	yes		51	yes - gender, age, BMI	patients undergoing surgery	hospital	n/a	no	no	ethics committee for human research at Londrina State university approval

Evers Larsson et al. (2003)	before and after	yes		57	yes - gender, age, BMI	participants in weight loss intervention programmes at the Karolinska hospital in Stockholm	hospital	n/a	no	no	local ethics committee approval
Gabriel et al. (2011)	randomised controlled trial - block randomised design	yes		508	yes - gender, age, BMI	direct mailing from selected ZIP codes in Allegheny County, Pennsylvania	University of Pittsburgh	no differences at baseline between groups	no	no	institutional review board at the University of Pittsburgh approval
Hortobagyi et al. (2011)	before and after	yes		20	yes - age, BMI	metabolic surgery patients at Pitt County Memorial hospital	East Carolina University	n/a	no	no	University and medical centre institutional review board at East Carolina University
Josbe	before	yes	physical	20	yes -	consecutiv		n/a	no	no	institution

no et al. (2010)	and after		activity was encouraged postoperatively but no formal exercise guidelines given - may increase physical function		gender, age, BMI	e participants scheduled for laparoscopic gastric bypass surgery					al review board approval
Lemoine et al. (2007)	cohort design	yes		40	yes - gender, age, BMI	referred by personal physician to a specialised institution located in the greater Toulouse are to participate in a weight reducing programme	Clinique du Chateau de Vemhes, Bondigoux, France	premenopausal women (n=13) younger than postmenopausal women (n=27)	no	no	university ethics committee on human research for medical sciences approval

Maniscalco et al. (2006)	before and after	yes		15	yes - gender, age, BMI	chosen from waiting list for laparoscopic adjustable gastric banding		n/a	no	no	local ethics committee approval
Plewa et al. (2007)	before and after	yes	patients encouraged to increase daily physical activity - no set exercise programme - may improve gait parameters	52	yes - gender, age, BMI			n/a	no	no	Senate ethics committee of the academy of physical education in Katowice approval

Sarsan et al. (2006)	randomised controlled trial - sealed envelopes	yes	diet not controlled, could affect weight loss	76	yes - gender, age, BMI	patients admitted to endocrinology and metabolic diseases department and seen by a physical medicine and rehabilitation department for exercise	exercise unit of physical medicine and rehabilitation department, university hospital	no differences at baseline between groups	no	no	signed informed consent
Stegen et al. (2011)	before and after, controlled	yes	patients chose intervention group they were in, those in exercise group more likely to participat	19	yes - gender, age, BMI	patients undergoing surgery	hospital	exercise group slightly younger, more females, higher BMI	no	no	Ghent university hospital ethics committee approval

			e in exercise after surgery								
Tompkins et al. (2008)	before and after	yes		30	yes - gender, age, BMI	patients scheduled for surgery	hospital	n/a	no	no	hospital and university's institutional review boards approval
Vargas et al. (2013)	before and after	yes		67	yes - gender, age, BMI	from reference centre for obesity treatment	hospital	n/a	no	no	committee on ethics in research of the institution under protocol no. 561/11
Vartiainen et al. (2012)	before and after	yes		18	yes - gender, age, BMI	recruited from clinical nutrition unit of Kuopio University hospital, Kuopio, Finland	gait laboratory	n/a	no	no	ethics committee of Kuopio university hospital approval

Lyytinen et al. (2013)	before and after	yes		18	yes - gender, age, BMI	from the unit of clinical nutrition at Kuopio university hospital, Finland	hospital	n/a	no	no	ethics committee of Kuopio university hospital approval
Bragge et al. (2014)	before and after	yes		18	yes - gender, age, BMI	recruited from clinical nutrition unit of Kuopio University hospital, Kuopio, Finland	gait laboratory	n/a	no	no	ethics committee of Kuopio university hospital approval
Vincent et al. (2012)	before and after, controlled	yes	some patients opted to join an exercise facility, may give more improvement in physical function	45	yes - gender, age, BMI	enrolled from weight loss centre	orthopaedics laboratory at a university hospital	control group slightly older, lower weight and BMI	no	no	investigational review board approval

	Outcome and Intervention								
Author and Date	**Specify frequency of outcome measurement**	**Outcome areas**	**List measures used**	**Were the outcome measures reliable?**	**Were the outcome measures valid?**	**Intervention described in detail?**	**Description of intervention**	**Contamination was avoided?**	**Cointervention was avoided?**
Castello et al. (2011)	pre, post (4 months)	heart rate variability, functional capacity	6MWT, heart rate, skinfold thickness, body circumferences, Baecke questionnaire - occupation, sport and leisure activities. Maximal exercise testing (1 month after surgery)	yes	yes	yes	roux-en-Y gastric bypass, training programme - 1 hour, 3 times/week - 5 mins stretching, 5 mins warm up, 40 mins exercise (speed and incline according to heart rate), 1 min recovery, 10 mins stretching	yes	Yes
De Souza et al. (2009)	pre, post (7-12 months)	functional capacity	6MWT	yes	yes	yes	roux-en-Y gastric bypass	yes	Yes

Evers Larsson et al. (2003)	pre, post intervention (12 weeks), post weight maintenance (64 weeks)	walking test, VO2 max	walking speed measured with speedometer, bicycle ergometer test	yes	yes	yes	very low calorie diet (330-420 kcal/day) or diet (1600 kcal/day) for 8-12 weeks, then 1600 kcal/day for 52-104 weeks	yes	Yes
Gabriel et al. (2011)	pre, post (6, 18, 30, 48 months)	physical activity, body composition	400m walk, modifiable activity questionnaire, waist circumference	yes	yes	yes	Health education controls - 6 lectures in year 1, then quarterly. Lifestyle change - dietary and physical activity changes from nutritionists, exercise physiologists, behavioural psychologists, 40 group visits in year	yes	Yes

							1, 12 monthly visits in year 2 and 3		
Hortobagyi et al. (2011)	pre, post (7 and 12.8 months)	gait biomechanics	temporal-spatial parameters, angular displacement, ROM, GRF, joint moments	yes	yes	yes	roux-en-Y gastric metabolic surgery	Yes	Yes
Josbeno et al. (2010)	pre, post (3 months)	physical activity, physical function, health related quality of life, pain and psychosocial factors that might influence physical activity	7 day physical activity recall questionnaire, pedometer, 6MWT, short physical performance battery - 4 m walk, standing balance, chair rise, short form 36 questionnaire, numeric pain rating scale, physical	yes	yes	yes	laparoscopic gastric bypass surgery	n/a	n/a

			activity self-efficacy questionnaire, physical activity barriers and outcome expectations questionnaire						
Lemoine et al. (2007)	pre, post (3 weeks)	physical condition, health related quality of life, eating behaviours	6MWT, SF-36, three factor eating questionnaire	yes	yes	yes	1400 kcal/day. 45 mins cycle ergometer endurance and 25 mins walking 6 days/week for 3 weeks	Yes	Yes
Maniscalco et al. (2006)	pre, post (1 year)	functional capacity	6MWT	yes	yes	yes	laparoscopic adjustable gastric banding surgery	n/a	n/a
Plewa et al. (2007)	pre, post (3 months)	gait biomechanics	temporal-spatial parameters	yes	yes	Yes	low calorie diet (1000-1200 kcal/day)	n/a	n/a

Sarsan et al. (2006)	pre, post (12 weeks)	weight, muscle strength, cardiovascular fitness, blood pressure, mood	beck depression inventory, 1 rep max, vo2 max on cycle ergometer, 6MWT	yes	yes	Yes	Aerobic - 15 min walk, 12-45 min cycle at 50-85% hear rate reserve (progressive). Resistance - 1-3 sets of 10 reps, 40-60% 1 rep max (progressive). Stretching before and after exercise.	yes	yes
Stegen et al. (2011)	pre, post (4 months)	physics performance battery - muscle strength, aerobic and functional capacity	1 rep max, handgrip strength and fatigue, sit to stand, 6MWT, maximal cardiopulmonary exercise	yes	yes	Yes	gastric bypass, 3 times/week for 12 weeks - 10 mins cardiovascular warm up, 25 mins strength training, 30 mins endurance training, 10 mins cool	yes	yes

							down		
Tompkins et al. (2008)	pre, post (3, 6 months)	physical function, health related quality of life	SF-36, 6MWT	yes	yes	Yes	gastric bypass surgery	n/a	n/a
Vargas et al. (2013)	pre, post (3months)	functioning and degree of motor and cognitive dependence	anamnesis, 6MWT, functional independence measure, timed up and go	yes	yes	Yes	roux-en-Y gastric bypass	n/a	n/a
Vartiainen et al. (2012)	pre, post (8.8 ± 4.2 months)	gait biomechanics	temporal-spatial parameters, angular displacement, ROM, joint moments	yes	yes	Yes	bariatric surgery	n/a	n/a
Lyytinen et al. (2013)	pre, post (8.8 ± 3.8 months)	health related quality of life, pain, physical function, properties of quadriceps femoris muscle	RAND-36, WOMAC, ultrasound, sock test, repeated sit to stand, stair ascent and descent, timed up and go, 6MWT	yes	yes	Yes	roux-en-Y gastric bypass	n/a	n/a
Bragge et al. (2014)	pre, post (8.8 ± 3.9	GRF	3D GRF, knee	yes	yes	yes	roux-en-Y gastric	n/a	n/a

	months)		accelerations				bypass surgery		
Vincent et al. (2012)	pre, post (3 months)	gait biomechanics, musculoskeletal pain, quality of life	temporal-spatial parameters, functional ambulatory profile, 6 m walking speed, SF-36	yes	yes	yes	18 roux-en-Y gastric bypass, 7 laparoscopic adjustable gastric banding	yes	yes

	Results								
Author and Date	**Results were reported in terms of statistical significance?**	**Outline of results**	**Were the analysis methods appropriate?**	**If not statistically significant was study big enough to show an important difference? (power and sample size)**	**Clinical importance was reported?**	**What was the clinical importance of the results?**	**Drop-outs were reported?**	**Reasons for drop-outs**	**How were drop-outs handled?**

Castello et al. (2011)	yes p<0.05	only training group had significant increase in heart rate variability, 6MWT after aerobic exercise training	Yes	power of 80%, confidence interval of 95%	yes	aerobic physical training can produce marked and faster benefits after surgery	yes, 11	refused to continue (5 in training group - 3 had trouble fitting in training, 2 had muscle/joint pain when exercising, 5 in control group - 3 lived in another city, 2 showed no interest continuing), died (control group)	results excluded drop outs
De Souza et al. (2009)	yes p<0.05	6MWT distance improved after surgery	Yes		no	6MWT can be used to assess functional capacity of severely obese individuals	yes, 2	not able to contact - change of address	51 vs 49

Evers Larsson et al. (2003)	yes p<0.05	improvements in BMI, self-selected walking speed, VO2 max/kg, heart rate, perceived exertion and relative oxygen cost of walking (% VO2 max)	yes		no	secondary benefits of weight loss, benefits remained even with partial weight relapse during maintenance period	yes, 14	pregnancy, side effects of diet programme, operation, not attending programme	results excluded drop outs
Gabriel et al. (2011)	yes p<0.05	increased leisure time physical activity and reductions in body weight, BMI, waist circumference and fat mass were associated with decreased walk time from baseline to 48 months	yes		yes	400 m walk can be used to measure cardiorespiratory fitness in lifestyle interventions and weight loss programmes	yes, 55	39 had missing 400 m walk data (undocumented), 6 did not complete 400 m walk due to personal time constraints or unavailability of corridor, 10 did not complete due to functional limitation	

Hortobagyi et al. (2011)	yes p<0.05	weight loss increased swing time, stride length, gait speed, hip ROM, max knee flexion and ankle plantar flexion, sagittal plane normalised knee moment increased and absolute ankle and frontal plane knee moments decreased	yes	small sample size	no	may be weight loss threshold of 30 kg limiting changes in gait kinematics	yes, 10	4 scheduling conflicts, 2 moved away, 1 involved in car accident, 3 lost interest in participation	results excluded drop outs
Josbeno et al. (2010)	yes p<0.05	Physical activity did not increase significantly. Average daily steps, 6MWT, short physical performance battery, physical function of SF-36, total SF-36 increased significantly. Numeric pain rating scale score decreased for low back, knee and	yes	small sample size	no	physical activity barriers were unchanged after surgery - focus on reducing barriers to physical activity in obese after surgery	yes	no dropouts	n/a

		foot/ankle							
Lemoine et al. (2007)	yes $p<0.05$	BMI and fat mass reduced. Distance walked increased. Restriction increased, disinhibition and susceptibility to hunger decreased. SF-36 mental component score increased. SF-36 physical component increased in postmenopausal women only	yes	small sample size	no	short term diet and physical activity intervention had favourable impact on body composition, physical condition, health related quality of life and eating behaviours irrespective of menopausal status	yes	no dropouts	n/a
Maniscalco et al. (2006)	yes $p<0.05$	mean BMI decreased postoperatively, distance walked increased, dyspnoea score after 6MWT was reduced, functional variables after	yes		no	weight reduction in obese increases functional capacity during walking	yes	no dropouts	n/a

		6MWT showed improvement							
Plewa et al. (2007)	yes p<0.05	After weight loss, obese women walked faster, made more steps per minute, stride length and swing duration increased. Cycle time, stance and double support phases were shortened	yes		no	reduction of body mass in obese individuals has positive effects on gait kinematics	yes	no dropouts	n/a
Sarsan et al. (2006)	yes p<0.05	resistance group showed improvement in 1 rep max, aerobic group had increased vo2 max and beck depression scale scores	yes		yes	Aerobic exercise improves depressive symptoms and max oxygen consumption, resistance exercise increases muscle strength in obese women. Both aerobic and resistance	yes, 6 resistance, 6 aerobic, 4 control	noncompliance, illness, lost to follow-up	results excluded drop outs

						exercise can result in a significant improved performance and exercise capacity in obese women			
Stegen et al. (2011)	yes p<0.05	Weight loss through surgery decreases dynamic and static muscle strength and no improvement in aerobic capacity. Exercise after surgery could prevent decrease and even induce an increase in strength, with an improvement in aerobic capacity, functional capacity	yes		no	exercise programme in the first 4 months after surgery is effective and should be promoted considering that physical fitness does not improve by weight loss only	yes, 2 control, 2 exercise	domicile distance, demanding job and household, education	results excluded drop outs
Tompkins et al. (2008)	yes p<0.05	6MWT distance improved after surgery (3 and 6 months), health related quality of	yes		no	Improved functional capacity was associated with	yes, 5	lost to follow-up, 4 did not participate in both follow-ups	results excluded drop outs

		life improved - physical and mental components of SF-36				enhanced health related quality of life. Enhance benefits after surgery with patient specific exercise programme and education on benefits of physical activity			
Vargas et al. (2013)	yes p<0.05	improvements in 6MWT, functional independence measure, timed up and go, weight and BMI after surgery	yes		no	recommending rehabilitation programmes for pre and post bariatric surgery	yes	no dropouts	n/a
Vartiainen et al. (2012)	yes p<0.05	decrease in step width at both gait speeds, no changes in relative double support or swing time or stride length, significant	Yes	small sample size	no	weight loss reduces hip and knee joint moments in proportion to the amount of weight lost	yes, 5	2 refused to participate in follow-up due to personal reasons, 2 failed to complete both walking speed tests, 1 had lost	results excluded drop outs

		decrease in absolute values of peak knee abductor, peak knee flexor, peak hip extensor moment, no change in normalised moments						GRF data	
Lyytinen et al. (2013)	yes p<0.05	improvements in physical function, physical functioning, physical role functioning and general health domain scores of RAND-36, subcutaneous fat thickness and absolute muscle thickness of quadriceps femoris decreased, fat and connective tissue proportion in quadriceps femoris muscle	Yes	small sample size	no	surgery had a positive impact on physical function but a negative impact on muscle structure	yes, 2	personal reasons	results excluded drop outs

		were increased after surgery							
Bragge et al. (2014)	yes p<0.05	absolute GRF parameters decreased in proportion to weight loss, medial lateral GRF parameters decreased more than expected, knee accelerations demonstrated lower impulsive loadings in axial and horizontal directions, no significant differences in stair walking	Yes	small sample size	no	weight loss after surgery induces a simple mass related adaption in gait and mechanical plasticity in gait strategy	yes,3	2 refused to participate in follow-up due to personal reasons, 1 failed to complete both walking speed tests	results excluded drop outs
Vincent et al. (2012)	yes p<0.05	Differences between 2 groups at 3 months in step length, base of support, single and double support. In surgery group low back and knee pain	yes	small sample size	no	improvements in some gait parameters, walking speed, quality of life and perceived functional limitations 3 months after	yes	no dropouts	n/a

		reduced, walking speed increased, reduced perceived limitations with walking and stair climbing, physical component SF-36 score increased				surgery			

	Discussion and Conclusion		
Author and Date	**Conclusions were appropriate given study methods and results?**	**What did study conclude? What are implications?**	**What were main limitations and biases in study?**
Castello et al. (2011)	yes	12 week aerobic exercise training programme improves cardiac autonomic modulation and functional capacity in obese women 4 months after surgery. Further study on effect on cardiovascular morbidity and mortality, longer term follow-up (e.g. 12 months)	functional capacity not assessed by ergospirometry
De Souza et al. (2009)	yes	Obese patients have reduced aerobic capacity, improvements after weight loss. 6MWT provides useful information about functional capacity of severely obese people	need to factor in age, gender, height and weight in 6MWT results
Evers Larsson et al. (2003)	yes	10% weight reduction by dieting in severely obese women improved walking speed, heart rate, and perceived exertion during walking	VO2 max from bicycle not treadmill, no reliable measures of leisure time physical activity

Gabriel et al. (2011)	Yes	Weight loss and positive healthy behaviour change improved physical function measured by 400 m walk. Support use of 400 m walk to measure physical function	relatively homogeneous population, walk time can be affected by gait abnormalities, lifestyle intervention funding stopped at 36 months - 12 months of no intervention
Hortobagyi et al. (2011)	Yes	Large weigh loss produced mechanical plasticity by modifying knee and ankle moment and gait behaviour. Further work to examine interactions between gait mechanics and gender, physical activity, clinical state of knee joint after surgery induced large weight loss	small sample size, marker placement, no non weight loss control group
Josbeno et al. (2010)	Yes	Weight loss improves physical function and health related quality of life and reduced pain. Limited improvement in physical activity - further research on barriers to physical activity to maximise weight loss maintenance and minimise chronic disease risk factors	lack of focus addressing barriers to physical activity
Lemoine et al. (2007)	Yes	Diet and physical activity intervention had favourable impact on body composition, physical condition, health related quality of life and eating behaviours irrespective of menopausal status. further studies with middle aged pre-menopausal and early post-menopausal women	short duration of intervention
Maniscalco et al. (2006)	Yes	Bariatric surgery consistently leads to improvement in 6MWT. 6MWT is a reliable and practical test to assess change in functional capacity	cannot determine max o2 consumption, couldn't exclude all comorbid conditions
Plewa et al. (2007)	Yes	Reduction of body mass in obese individuals has positive effects on gait kinematics, even though treatment was only 3 months there were significant changes in all gait parameters tested. Further research to include ground reaction forces, electromyography to find underlying cause of observed gait changes after weight reduction process	not complete gait analysis

Sarsan et al. (2006)	Yes	Both aerobic and resistance exercise resulted in improved exercise capacity in obese women who were not on an energy restricted diet. Resistance exercise more effective in improving muscle strength, aerobic exercise more effective in improving mood and max oxygen consumption. further long term follow-up studies needed	only applies to women cannot be generalised to men, no data about what happened after the end of the programme
Stegen et al. (2011)	Yes	Weight loss through surgery results in decreased dynamic and peripheral static muscle strength and no improvement in aerobic capacity, most components of functional capacity did not improve. Endurance and resistance exercise programme could prevent decrease and even induce an increase in strength, improve aerobic capacity and functional capacity. exercise training programme in first 4 months after surgery is effective and should be promoted	Patients who were more likely to do exercise would have chosen to be in exercise group, vice versa.
Tompkins et al. (2008)	Yes	Patients had rapid improvement in functional walking distance after surgery. Provide indexes of functional capacity in people with morbid obesity before and after surgery.	small sample size although represented of population, from limited geographic region, not enough data from 6MWT to give normative data for population
Vargas et al. (2013)	Yes	Obesity has an impact on the functioning and quality of life of patients. Improvements in 6MWT, functional independence measure, timed up and go after bariatric surgery. Linear relationship between reduction of BMI and increased functioning.	no control group
Vartiainen et al. (2012)	Yes	Hip and knee moments are reduced in proportion to weight lost and step width reduced. Further studies to see if these changes reduce emergence of new knee osteoarthritis cases.	validity in marker placement in obese and after weight loss, soft tissue movement artefact, no zero angle calibration for knee and hip

Lyytinen et al. (2013)	Yes	Surgery has a beneficial and positive impact on physical function, subcutaneous fat thickness of quadriceps femoris muscles and subjects perception of health. Negative effect on quadriceps femoris muscle thickness and cross sectional area and fat and connective tissue proportion. need longitudinal studies to see if further benefits from further weight loss, need larger study population, further studies on effects of physical activity interventions after surgery to reduce fat and increase muscle mass	small sample size, mostly women
Bragge et al. (2014)	Yes	GRF parameters decreased in proportion to weight loss - simple mass driven changes in gait after weight loss, accelerations in lower extremities decreased significantly - smoother ground contact, decrease in skin mounted accelerometer parameters - mechanical plasticity in gait after weight loss. larger and longer prospective studies needed to evaluate surgery induced weight loss on knee osteoarthritis progression and reduction of new cases	didn't use self-selected speed, small sample size, may need longer follow-up period
Vincent et al. (2012)	Yes	Surgery gives rapid improvements in weight, joint pain, gait, walking speed, contribute to better self-perception and quality of life - facilitate participation in regular physical activity for continued weight loss and joint health. Further study should consider controlling for disability status	small sample size, surgery group had lifestyle choice guidance during pre and post visits,