The biomechanics of adiposity – structural and functional limitations of obesity and implications for movement

A. P. Hills1, E. M. Hennig2, N. M. Byrne3 and J. R. Steele4

1School of Human Movement Studies, Queensland University of Technology, Queensland, Australia. 2Biomechanik Labor, Universitaet Essen, Essen, Germany. 3Department of Nutrition Sciences, University of Alabama at Birmingham, Alabama, USA. 4Department of Biomedical Science, University of Wollongong, New South Wales, Australia.

Received 2 July 2001; revised 25 September 2001; accepted 26 September 2001

Address reprint requests to: AP Hills, PhD, School of Human Movement Studies, Queensland University of Technology, Victoria Park Road, Kelvin Grove, Queensland 4059, Australia.
E-mail: a.hills@qut.edu.au

Summary

Obesity is a significant health problem and the incidence of the condition is increasing at an alarming rate worldwide. Despite significant advances in the knowledge and understanding of the multifactorial nature of the condition, many questions regarding the specific consequences of the disease remain unanswered. For example, there is a dearth of information pertaining to the structural and functional limitations imposed by overweight and obesity. A limited number of studies to date have considered plantar pressures under the feet of obese vs. non-obese, the influence of foot structure on performance, gait characteristics of obese children and adults, and relationships between obesity and osteoarthritis. A better appreciation of the implications of increased levels of body weight and/or body fat on movement capabilities of the obese would provide an enhanced opportunity to offer more meaningful support in the prevention, treatment and management of the condition.

Keywords: Biomechanics, gait, obesity.

Introduction

Prevalence of overweight and obesity and related musculoskeletal problems

Obesity is recognized as a major health problem in many parts of the world and the incidence of the condition is escalating at an alarming rate (1,2). This global trend of increasing obesity prevalence indicates that current measures in the prevention, treatment and management of the condition are ineffective (3). Obesity significantly increases the risk of developing numerous medical conditions, including hypertension, stroke, respiratory disease, type 2 diabetes, gout, osteoarthritis, certain cancers and various musculoskeletal disorders, particularly of the lower limbs and feet (4,5). Despite significant advances in the knowledge and understanding of the multifactorial nature of the condition, many questions regarding the specific consequences of the disease remain unanswered.

Relative to the extensive literature now available on many aspects of the obese condition there is a dearth of information pertaining to the structural and functional limitations imposed by overweight and obesity. Subjective references have been made to the difficulties encountered by the overweight and obese when executing simple activities of daily living (6,7). However, the implications of persistent obesity on the musculoskeletal and locomotor systems, particularly during weight-bearing tasks such as walking and stair-climbing, are poorly understood (8–11). To date, the study of locomotor tasks has focused predominantly on normal-weight individuals and particularly those without physical disabilities associated with obesity. The limited number of studies focusing on obese individuals published to date encompass the locomotor characteristics of obese children (6,8–11) and adults (12), studies of plantar pressures under the feet of the obese (13,14), the influence of obesity on foot structure and functional performance of children (7,14–16), and

© 2002 The International Association for the Study of Obesity. obesity reviews 3, 35–43
potential relationships between obesity and osteoarthritis (12,17).

The primary aim of this article is to review the current literature pertaining to the effects of overweight or obesity on structure and function. Some of the key issues that may challenge the overweight and obese when completing activities of daily living are considered, including the most fundamental of voluntary movement patterns, walking. Owing to the enormity of the problem of obesity, and the relative paucity of information available, there is an urgent need to focus greater attention on the physical consequences of repetitive loading of major structures, particularly in the lower extremity. Throughout this article key questions are posed as areas of importance for future research.

**The effects of obesity on musculoskeletal structure and function**

**Foot structure and function**

The feet, as the base of support of the body, are continually exposed to high ground reaction forces generated during activities of daily living. Various authors have suggested that excessive increases in weight-bearing forces caused by obesity may be detrimental to the lower limbs and feet. Despite the potential negative consequences of obesity on lower limb structure, only limited research has considered the effects of obesity on foot structure in obese individuals (14,15). These studies have indicated that obese pre-pubescent children have significantly flatter feet than their non-obese counterparts. It is unknown whether the greater prevalence of flatfootedness in obese children is a result of the presence of a fat pad that remains or develops in their instep, thereby causing a form of flatfeet that may have no negative consequences. However, it is also unknown whether excessive weight bearing has caused some structural dysfunction, such as a collapse of the longitudinal arch, thereby resulting in an increased midfoot contact area that could have pathological consequences (15). Dowling & Steele (18) recorded 26 anthropometric measurements for the right and left leg/foot of 10 obese [age = 8.8 ± 2.0 years; body mass index (BMI) = 25.8 ± 3.8kg m⁻²] and 10 non-obese children [age = 8.9 ± 2.1 years; BMI = 16.8 ± 2.0kg m⁻²], who were matched to the obese children for age, height and gender, to characterize the external shape of these children’s feet. Significant effects of obesity were noted on 16 of the 26 anthropometric variables, whereby the parameters measured for the obese subjects’ legs/feet were significantly larger than those calculated for their non-obese counterparts. Whether these changes in foot structure may develop into symptoms if excessive weight gain were to continue and, in turn, hinder participation in physical activity in either childhood or adulthood, is speculative and requires further investigation.

Furthermore, as the foot structure of obese children has only been indirectly assessed to date, further research to directly measure the effects of obesity on foot structure in both children and adults is also recommended.

**The plantar fat pad**

The plantar fat pad is specially organized adipose tissue that provides cushioning to the underlying foot structures. It is believed to be important for protection of the foot during ambulation and in the prevention of heel pain (19,20). Comparing 70 patients with plantar heel pain with 200 normal subjects, Prichasuk (21) reported that the BMI was greater in the subjects with heel pain. Jorgensen & Bojsen-Møller (22) reported that thinner heel fat pads display a reduced ability to absorb shock. Nass et al. (23) investigated the heel pad properties in overweight subjects. From 35 normal and 16 overweight persons (BMI > 27), ultrasound heel pad thickness scans were performed at five static loading conditions (10, 25, 50, 75 and 100% of body weight). Heel pad thickness increased as a function of BMI while the compressibility index of the heel pad did not differ between the groups. Based on these findings it would appear that, if thickness and the compressibility index are indicators of protective properties of the heel pad, overweight subjects are not disadvantaged by their heel pad structures in terms of protecting their feet during ambulation. An analysis of plantar peak pressures, however, showed significantly increased values at the heel for the overweight group. Mechanical and polymodal nociceptors are widely distributed in the skin to provide information on pain perception. Greeenspan et al. (24) reported that through spatial summation of applied pressures a decrease in pain threshold with an increased field of stimulation is caused. Comparing pain perception with averaged plantar pressures, Hodge et al. (25) reported significant positive correlations between pressure magnitude and the pain ratings. From these findings and the results of their study, Nass et al. (23) hypothesized that an increase of foot pressures (and not a change in heel pad properties) leads to a higher likelihood of the development of plantar heel pain.

**Plantar pressures and obesity**

It would seem obvious that increased body weight would result in higher plantar foot pressures. However, in a study of standing and walking in 111 non-obese adults (26), surprisingly few relationships between pressures under the foot and body weight were found. The authors concluded that an increase in foot dimensions, as well as a redistribution of plantar loads from areas of high pressures towards areas of lower pressures, was the cause of this surprising result. Only during walking did the 49 female subjects show a moderate relationship between body weight and...
peak pressures under the midfoot \((r = 0.68, p < 0.01)\). As the male subjects did not demonstrate this effect it was postulated that weaker ligaments in the feet of the women contributed to the increased collapse of the longitudinal arch when subjected to the dynamic loads in walking. Measurements with toddlers between 14 and 32 months of age (27), and a study with 125 school children between 6 and 10 years of age (28), provided data on plantar pressures in various developmental stages in non-obese children.

Dowling et al. (14) investigated the effects of obesity on the plantar pressures generated by 13 obese (BMI: 25.5 ± 2.9 kgm\(^{-2}\)) and 13 non-obese (BMI: 16.9 ± 1.2 kgm\(^{-2}\)) pre-pubescent children, matched to the obese children for gender, age and height. The obese pre-pubescent children generated significantly higher pressures under the forefoot during walking compared to their non-obese counterparts. These results were confirmed again by Dowling (29) who identified that obese children (BMI: 25.8 ± 3.8 kgm\(^{-2}\)) generated significantly higher dynamic mean peak pressures and pressure-time integrals, particularly under their midfoot and especially under the metatarsal heads II to IV (see Fig. 1). The author postulated that these obese children might be at an increased risk of developing pathologies in this area of the foot, such as stress fractures of the forefoot or skin ulceration as a result of increased pressures being borne by the small bones of the forefoot. Furthermore, foot discomfort associated with this increased forefoot plantar pressure in obese children may hinder their participation in physical activity as weight-bearing activities can be ‘uncomfortable’ if not appropriately designed to account for these structural characteristics.

A recent study (13) investigated the effect of obesity in 35 women (BMI = 17.1–48.4 kgm\(^{-2}\)) and 35 men (BMI = 20.0–55.8 kgm\(^{-2}\)) on plantar pressures during standing and walking. Using a BMI value of 28 as the cut-off, 19 women and 19 men were categorized as being overweight. In both gender groups, foot width during standing was significantly greater in the overweight subjects. However, no significant differences in foot length were detected. Both overweight gender groups had increased pressure values under all anatomical locations of the foot during standing. For walking, the two overweight groups also showed higher pressures under the heel, midfoot and the metatarsal heads II to IV (see Fig. 2). Comparisons of the standing and walking data showed stronger relationships between BMI and plantar pressures during dynamic loading of the foot. A subset of the 38 overweight subjects (six women and three men) succeeded in losing a substantial amount of body weight (19.4 kg or 19.6% of their original body weight) during a subsequent weight-reduction programme. As a function of weight loss, reductions in the peak plantar pressures were observed under the midfoot and especially under the metatarsal heads (30).

Muscular strength and power

Inadequate muscular strength and/or power, particularly of the lower limbs, can also impair motor function, limiting individuals from successfully performing everyday tasks and predisposing them to a greater risk of musculoskeletal fatigue and/or injury. Riddiford et al. (16) investigated the effects of obesity on the strength and power of 43 obese (BMI: 24.1 ± 2.3 kgm\(^{-2}\)) and 43 non-obese (BMI: 16.9 ± 0.4 kgm\(^{-2}\)) healthy, pre-pubescent children (8.4 ± 0.5 years). Age-appropriate field tests of a basketball throw for distance, arm push/pull ability, and vertical and standing long jump performance, were used. Although obesity did not negatively impact upon upper limb strength or power in these activities, it impeded the children’s ability to perform tasks involving lower limb strength and power in which the obese children were required to move their larger mass against gravity. That is, the obese children were disadvantaged in both standing long jump and vertical jumping tests by the need to apply a greater force to accelerate their larger mass against gravity a given distance. As decreased muscular strength and power may affect the ability of children to learn and successfully perform activities of daily living, particularly during their developmental years, this finding was of concern. Similar findings have been reported by Hills & Parker (31). Further research is warranted to identify a wider range of activities in which obesity has a negative impact. This work would be of particular relevance in the design of appropriate intervention strategies.

Walking gait and other activities of daily living

Walking is a fundamental movement pattern, the most common mode of physical activity. However, walking is an
extremely complex biomechanical process, involving an interplay between muscular and inertial forces (32–34). The quality of gait is associated with the structural and functional constraints imposed by the locomotor system, the ability to implement an effective motion strategy, and the individual’s metabolic efficiency (35). One of the potential challenges to the ‘normal’ pattern of walking in the overweight and obese is the need to carry excess body weight (or body fat) over the long term. There is a general paucity of detail in the research literature specifically regarding the interplay between metabolic and mechanical costs of walking. Furthermore, no attention has been paid to locomotor characteristics across various levels of body weight and body fat. A leading question that arises then is whether excess body weight or excess adiposity is a major limiting factor in movement. In tasks such as walking, the structural

Figure 2 Peak plantar pressures (kPa) during walking for obese (O) vs. non-obese (N) men and women (13). *P < 0.05, **P < 0.01. This figure is reproduced from Int J Obes 2001; 25: 1674–1679 with permission from Nature Publishing Group.
(mechanical) and functional (physiological) cost of the activity are important determinants of a person’s movement capacity (and therefore limitation) and physical fitness. The interplay of these characteristics also contributes to the rate of fatigue in physical activity, including activities of daily living. Furthermore, the intensity and energy equivalence of physical activities are important elements within an exercise prescription for the obese (36). Differentials in energy cost and exercise intensity among people whose body composition (specifically, fat mass and fat-free mass ratio) varies have consequences for subsequent individualized prescriptions (A. P. Hills & N. M. Byrne, unpublished).

The sustained repetition of load cycles in walking make significant demands on the musculoskeletal apparatus in normal-weight individuals (37). How then does the carriage of excess body weight (or body fat) accentuate such demands in the obese? What additional loading forces may be experienced by the obese as a function of excess body weight (or body fat)? In addition to increased loading on major joints as a function of excess weight (body fat), does efficient mechanics also contribute to increased energy expenditure in the obese when they are engaged in the same movement task as lighter counterparts? Is there an individual threshold of size and shape (or body composition status) above which potential disruption to the musculoskeletal system is greater?

Detailed analyses of the gait characteristics of obese children (8–11) and, to a lesser extent, adults (12), has helped provide a clearer understanding of movement-related difficulties experienced by the obese. An evaluation of gait over time may also provide an indication of the potential problems with the persistence of obesity. During normal walking the major joints of the lower extremity are exposed to considerable loads (38,39) with joint reaction forces of approximately three to five times body weight (40). Participating in movement tasks such as stair climbing, jogging and running involves joint reaction forces at the higher end of this range and beyond. Based on Newtonian Laws of Motion it would appear reasonable to hypothesize that obese individuals will experience greater loads on their joints than normal-weight individuals. However, to date the joint forces generated by obese individuals during walking have not been documented. Will the loads experienced at major joints increase when the obese individual attempts to move at speeds that are different from the normal, preferred pace of walking?

For all individuals, irrespective of size and shape, a comfortable self-selected free speed of walking is commonly less variable than any imposed walking speed. That is, the gait of a mature, normal-weight individual is characterized by the ability to display consistency across various speeds of walking. Many growing children, but more commonly obese children, display considerable disruption to normal temporal characteristics when walking more slowly or faster than their normal, invariant base pattern. Hills & Parker (9) noted that obese pre-pubertal children showed greater asymmetry in gait than non-obese children, consistently favouring the right limb. Ease of walking at a self-selected speed and the difficulty of overriding a natural cadence is a well-documented phenomenon in normal adults. More research is needed to determine the variability in temporal patterning and the ability of children and adults at different levels of adiposity to adjust to changes in walking speed. The additional adiposity of the obese and duration in the obese state may be important factors governing such individuals’ ability to adjust to changes in walking speed.

In addition to a compromised ability to adjust to changes in walking speed, several temporal characteristics differ between obese and normal-weight pre-pubertal children (8). For example, obese children have a longer stance phase and slower speed of walking, as reflected by a longer cycle duration, lower cadence and lower relative velocity (statures/s). These findings confirm the common qualitative view of a slower, safer and more tentative walking gait in obese children relative to normal-weight children.

More unstable individuals, including the obese, display a longer double- and a shorter single-limb support period (8,9). Parker et al. (41), in a study of Down’s syndrome children who were overweight, reported a higher-than-normal percentage of the gait cycle spent in support. As for the obese children in the studies by Hills & Parker (8,9), the greater support time of these children reinforces the safer and more tentative ambulation that reduces the non-support period and potential for instability.

Walking is a central component of gross motor development and the quality of walking is related to the level of maturity of the individual (33,42,43). There is an urgent need to conduct further research in this area, to develop a normative database on obese children and enable additional comparisons with non-obese children of similar stature and age. Determining the influence of speed of walking on children during the growing years to physical maturity is also warranted. Such normative data could form the basis for more effective intervention strategies to combat obesity in children. In summary, the obese typify an unreliability of gait patterning that is related to body composition and is affected by speed of walking.

In addition to walking, another activity of daily living that is performed repeatedly is rising to stand after sitting in a chair. Adults (aged 23–41 years) rise an average of 90 times daily (44). In young healthy persons, rising from a chair should be achieved with ease. However, recent research has indicated that when 8–9-year-old children were required to move their larger body mass against gravity to perform this basic daily task, obesity impeded their functional capacity. In fact, 69% of the obese children required assistance from the researchers to successfully
stand (45). The authors postulated that difficulty experienced by the obese children in rising was a result of insufficient lower limb strength to move their excess body mass upright against gravity. This movement difficulty may perpetuate the cycle of obesity by encouraging sedentary behaviour (remaining seated) for prolonged periods. However, the effects of obesity on the frequency and difficulty associated with the performance of activities of daily living are not documented. Are obese children and adults likely to have difficulty performing other activities of daily living in which they are required to raise their larger body mass against gravity, such as getting out of bed or rising from the toilet? If performing these activities of daily living is more difficult, do obese individuals avoid attempting them as frequently, in turn resulting in reduced energy expenditure and an increased likelihood of a positive energy balance?

**Obesity and osteoarthritis**

**The epidemiology of osteoarthritis**

Osteoarthritis is a degenerative disease and a comorbid condition of obesity affecting an increasing proportion of the population (46,47). It is a complex disease, the aetiology of which bridges biomechanics and biochemistry. Evidence is growing for the role of systemic factors, such as genetics, diet, oestrogen use and bone density, and local biomechanical factors (such as muscle weakness, obesity and joint laxity). These risk factors are particularly important in the weight-bearing joints, and modifying them may help to prevent osteoarthritis-related pain and disability (47).

Unfortunately, as is the case for movement characteristics of the obese, we have a relatively poor understanding of the inter-relationships between osteoarthritis and excess body weight (or body fat). However, obesity has consistently been identified as a risk factor for osteoarthritis of weight-bearing joints (48) and the progression of the condition is reported as being more rapid in the overweight and obese. For example, persistent loading of the musculoskeletal system in locomotor tasks such as walking has been implicated in the predisposition of the obese to knee osteoarthritis. The condition has also been recognized as a cause of significant disability (49,50). Furthermore, it has been suggested that the risk of osteoarthritis may be related to excess total body weight (and/or body fatness) rather than to the distribution of body fat and predisposition to metabolic conditions such as type 2 diabetes, characterized by a central concentration of adiposity.

The effectiveness of exercise in the treatment of osteoarthritis (51) is also poorly understood, although a number of studies have illustrated that disability is reduced in osteoarthritic patients who engage in regular physical activity (52,53). No studies have considered dose–response relationships between aerobic or resistance exercise (51). Therefore, it is not surprising that studies considering the potential improvement of osteoarthritic characteristics in obese subjects exposed to a controlled weight-loss intervention have been extremely limited. Felson et al. (54) reported that weight loss in middle-aged and older women significantly reduced the incidence of symptomatic osteoarthritis of the knee, but this study did not consider the efficacy of weight loss in subjects with existing osteoarthritis.

Messier et al. (17) have completed one of the few studies to determine if a combined dietary and exercise intervention would result in significant weight loss in older obese adults with knee osteoarthritis. The group also compared the effects of exercise plus dietary therapy with exercise alone on gait, strength, knee pain, biomarkers of cartilage degradation and physical function. Significant improvements were noted in both groups in self-reported disability and knee pain intensity and frequency, as well as in physical performance measures. However, no statistical differences were found between the two groups at six months in knee pain scores or self-reported performance measures of physical function and knee strength. In summary, weight loss was achieved and sustained over a six-month period in a cohort of older obese persons with osteoarthritis of the knee through a dietary and exercise intervention. Both exercise and combined weight loss and exercise regimens led to improvements in pain, disability and performance. Moreover, the trends in the biomechanical data suggest that exercise combined with diet may have an additional benefit in improved gait compared with exercise alone. A larger study is indicated to determine whether weight loss provides additional benefits over exercise alone in this population of patients.

It is interesting to speculate on the impact of sustained overweight and obesity on the predisposition to, and progression of, deterioration of articular cartilage and subchondral bone in adults. Similarly, what is the relationship between age of onset of obesity and predisposition to osteoarthritis? Is the period of time one has been obese a significant factor in the development of osteoarthritis? Does the persistence of overweight and obesity from childhood and adolescence into adulthood and body composition factors result in a presentation of osteoarthritic symptoms in progressively obese individuals?

Body composition changes as a function of ageing, in particular fat mass increases and lean body mass (LBM) decreases (55–59). Reductions in LBM will probably be paralleled with decreases in muscle mass, muscle strength and functional capacity (12). Syed & Davis (60) have suggested that ageing may be a primary risk factor for osteoarthritis because of age-related reductions in the muscle strength of key leg muscles and increases in body...
weight. Repeated impulse loading leads to stiffening of the bone, and a reduced period of eccentric quadriceps tension at heel strike in gait results in less effective shock absorbency (12). Weakness of the quadriceps may therefore be considered an aetiologic factor in the pathogenesis of knee osteoarthritis (61). A mechanism through which this may occur could involve the combination of muscle fatigue and changes in ground reaction forces that result in detrimental increases in the rate of loading on the knee joint (60). Support for this notion comes from data which shows that muscle strengthening, as a part of treatment, reduces disability (62).

While older females are consistently noted to be more likely than their male counterparts to suffer from knee osteoarthritis (63–65), no relationship exists between osteoarthritis and oestrogen use in women (66). The gender difference in the prevalence of knee osteoarthritis may be attributed to differences in body composition, with a higher proportion of body fat in women. Males commonly display a greater proportion of body weight as lean mass, and more importantly more muscle mass, and may benefit from greater musculoskeletal support and increased shock absorption potential during walking. While Syed & Davis (60) extend this argument further to suggest that knee osteoarthritis may be linked to quadriceps fatigue with long-duration (20 min) walking, there is no empirical evidence to support this proposal.

What is the long-term influence of obesity on musculoskeletal structure and function?

Obese adults who have been obese from childhood may face a compendium of medical problems (67). Many of the orthopaedic conditions that are manifested in obese adults may be the consequence of an excessive and prolonged loading of tissues. Owing to the progressive nature of such developments, it may be reasonable to hypothesize that younger individuals who have been obese for a relatively shorter period of time would be less likely to display orthopaedic anomalies related to the locomotor apparatus that are more commonly seen in older counterparts. However, this review has confirmed that even young, pre-pubertal children display evidence of alterations to both their musculoskeletal structure and function as a consequence of excessive weight bearing. Therefore, to minimize joint deterioration from excessive joint loading, any malalignment or malfunctioning of the lower limbs evident in obese children should be treated at the earliest possible opportunity (68).

Conclusions

The maintenance of functional mobility should be one of the highest priorities in the management of an obese individual, with or without comorbid conditions. High levels of body fat plus increased loads on the major joints has the potential to lead to pain and discomfort, inefficient body mechanics and further reductions in mobility. Efficiency of movement may be improved with an appropriate prescription of aerobic activity and resistance weight training, and interventions to improve gait, posture and balance. An understanding of locomotor characteristics and biomechanical efficiency concurrent with metabolic efficiency during the performance of daily living tasks would greatly assist the clearer understanding of movement-related difficulties of the obese.

References


