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WHAT IS THE IMPACT OF EXCESSIVE BODY MASS ON THE BIOMECHANICAL WALKING CHARACTERISTICS IN 7 TO 11 YEAR OLD CHILDREN?

STEPHEN DAVID COUSINS

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ABSTRACT

Childhood obesity is associated with multiple health co-morbidities and various musculoskeletal disorders, affecting the lower limb and feet. Limited research has been undertaken which quantifies the impact of obesity on the function of the paediatric foot and lower limb. Furthermore, it is yet undetermined whether overweight children display similar functional changes as their obese counterparts. The primary aim of this research was to advance understanding on foot function and lower limb biomechanical movement characteristics in children; analysing differences between obese, overweight and normal weight children.

Having determined the reliability of the measurement protocols, 100 children were recruited for assessment of body mass status and plantar foot loading. Following this, a sub-group of 45 children were recruited and three-dimensional gait analysis was undertaken. Plantar foot loading and lower limb temporal-spatial, kinematic and kinetic gait characteristics were analysed during barefoot level walking. Multiple regression was undertaken to determine relationships between body mass status, foot loading and lower limb gait biomechanics.

Findings demonstrated that overweight and obese children displayed marked differences in foot loading and lower limb gait biomechanics when compared to normal weight children. The research identified that increased loading at the midfoot and 2nd-5th metatarsals significantly predicted change in the kinematic and kinetic walking parameters at the hip and ankle in overweight and obese children. These findings provide evidence of an atypical biomechanical function of the foot and lower limb.

This work advances understanding on the implications of excessive body mass on the functional characteristics of the paediatric foot and lower limb. This research identifies for the first time, differences in foot loading and lower limb gait biomechanics in overweight and obese children relative to those of normal weight. This work also provides important information as to the use of plantar pressure assessment in predicting change to the lower limb biomechanical movement characteristics of these children. This work underpins the need for further longitudinal work that further enhances our understanding on the consequences of excessive body mass on the foot and lower limb musculoskeletal and locomotor systems in children.

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ABBREVIATIONS

HSE	Health Survey for England
NCMP	National Child Measurement Programme
ADP	Air Displacement Plethysmography
DEXA	Dual-energy x-ray Absorptiometry
MRI	Magnetic Resonance Imagery
BMI	Body Mass Index
BIA	Bioelectrical Impedance Analysis
IOTF	International Obesity Task Force
TEM	Technical Error of Measurement
i-FAB	International Foot and Ankle Biomechanics Community
ICCs	Intraclass Correlation Coefficient
CoV	Coefficient of Variation
MLA	Medial-longitudinal Arch
FA	Footprint Angle
CSI	Chippaux-Smirak Index
CMCs	Coefficients of Multiple Correlation
BMI-SDS	Body Mass Index Standard Deviation Score
LH	Lateral Heel
MH	Medial Heel
MID	Midfoot
1MTPJ	1st Metatarsophalangeal Joint
2-5MTPJ	2nd-5th Metatarsophalangeal Joint
TOES	2nd-5th Toes
IDS	Initial Double Support
SS	Single Support
TDS	Terminal Double Support
SW	Swing
SD	Standard Deviation
ANOVA	One-way Analysis of Variance Test
VIF	Variance Inflation Factor

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CHAPTER ONE: INTRODUCTION

Research is essential for improving the health outcomes of children (Lorenc et al. 2008). With the prevalence of childhood obesity increasing rapidly worldwide and emergence as a major health problem, it is important to evaluate the impact of excessive body mass on musculoskeletal structure and function in children. Childhood obesity is linked to multiple co-morbidities affecting multiple body systems, with growing evidence proposing that it can have a detrimental influence on the structure and function of the foot, as well as preventing normal movement patterns that predispose children to musculoskeletal pain and injury. However, due to gaps in the current literature the implications of childhood obesity on the lower limb musculoskeletal and locomotor systems, particularly during weight bearing tasks, are still poorly understood. The challenge with forming a consensus on the impact of obesity currently limits advances with care provision.

This work focuses on foot function and lower limb biomechanical movement characteristics in children; analysing differences between obese, overweight and normal weight children. Current research suggests that obese children are at an increased risk of developing foot discomfort and/or pathologies as a result of the increased forces acting upon the immature foot (Dowling et al. 2004; Mickle et al. 2006). It has also been suggested that obese children display altered temporal-spatial and lower limb kinematic and kinetic gait characteristics (McMillan et al. 2010; Morrison et al. 2008; Schultz et al. 2009). These changes may place the obese child at an increased risk of developing lower extremity discomfort or pathologies that may affect their ability to successfully perform activities of daily living and hinder their participation in physical activity, particularly during developmental years. However, despite the negative effect of obesity on paediatric foot and lower limb function; the full impact of these changes remains unclear.

In the past few decades the prevalence of overweight children has increased worldwide, alongside childhood obesity. This escalation is a cause for concern when it is considered that the vast majority of these children go on to become obese and remain obese in adulthood (The Health and Social Care Information Centre, 2012). One of the flaws with existing research is that it often fails to include overweight children within its sample, sometimes combining overweight and obese groups and/or using the definition interchangeably. As a result, the impact of being overweight on the biomechanical function of the paediatric foot and lower limb is unclear. Further work is essential to determine whether earlier invention is required, as early prevention and intervention may be key to mitigating against health co-morbidities associated with childhood obesity. Furthermore, few studies have presented a comprehensive analysis of the foot loading characteristics during walking in obese, overweight and normal weight children or developed a comprehensive three-dimensional approach to its gait analysis of obese and overweight children in determining how their gait compares to that of their normal weight peers. Finally, to the authors' knowledge, no study to date has investigated the relationship between body mass, altered characteristics of foot loading and altered lower limb gait biomechanics in children. Current research has focussed upon investigating either the effects of childhood obesity on foot loading characteristics or the effects of childhood obesity on the biomechanics of the lower limb during gait without establishing a relationship between the two.

With the increased prevalence of overweight and obesity among children, it is essential that further work be conducted in order to evaluate the full impact of excessive body mass on the functional characteristics of the paediatric foot and lower limb. A greater understanding of the implications of childhood overweight and obesity on foot loading and lower limb biomechanical movement characteristics of children will emerge from this work. This information will help to identify potential foot pathologies and movement related difficulties as musculoskeletal co-morbidities of the paediatric foot and lower limb (associated with obesity) may alter foot function and gait characteristics before they are diagnosed. Therefore, detecting functional changes to the foot and lower limb could reduce future incidence of musculoskeletal co-morbidities occurring. This research could also provide useful information for researchers and clinicians as to the use of plantar pressure assessment tools and three-dimensional motion analysis in assessing lower limb function in children that could then be used as a foundation to inform clinical care in the first line of assessment when evaluating functional characteristics of the lower extremity.

1.1 Studies within the Research Project

This research was comprised of three main studies.

1.1.1 Study One: Establishment of the Measurement Protocols

This study aimed to determine the within- and between-session reliability of the measurement protocols for the assessment of body mass status, foot loading and lower limb gait characteristics in children aged 7 to 11 years (Chapter Four, page 87).

1.1.2 Study Two: Assessment of Foot Loading during Level Walking

This study investigated alterations in the foot loading characterisitics of obese, overweight and normal weight children, aged 7 to 11 years, during barefoot level walking and also looked to determine the use of cluster analysis in identifying groups of participants with similar foot loading characteristics (Chapter Five, page 100).

1.1.3 Study Three: 3-D Gait Analysis of the Lower Limb during Level Walking

This final study utilised three-dimensional gait analysis, in order to identify differences in temporal-spatial and lower limb kinematic and kinetic walking patterns in obese, overweight and normal weight children, aged 7 to 11 years. The relationship between foot loading and lower limb kinematic and kinetic walking patterns of obese and overweight children will also be investigated during this phase of work (Chapter Six, page 120).

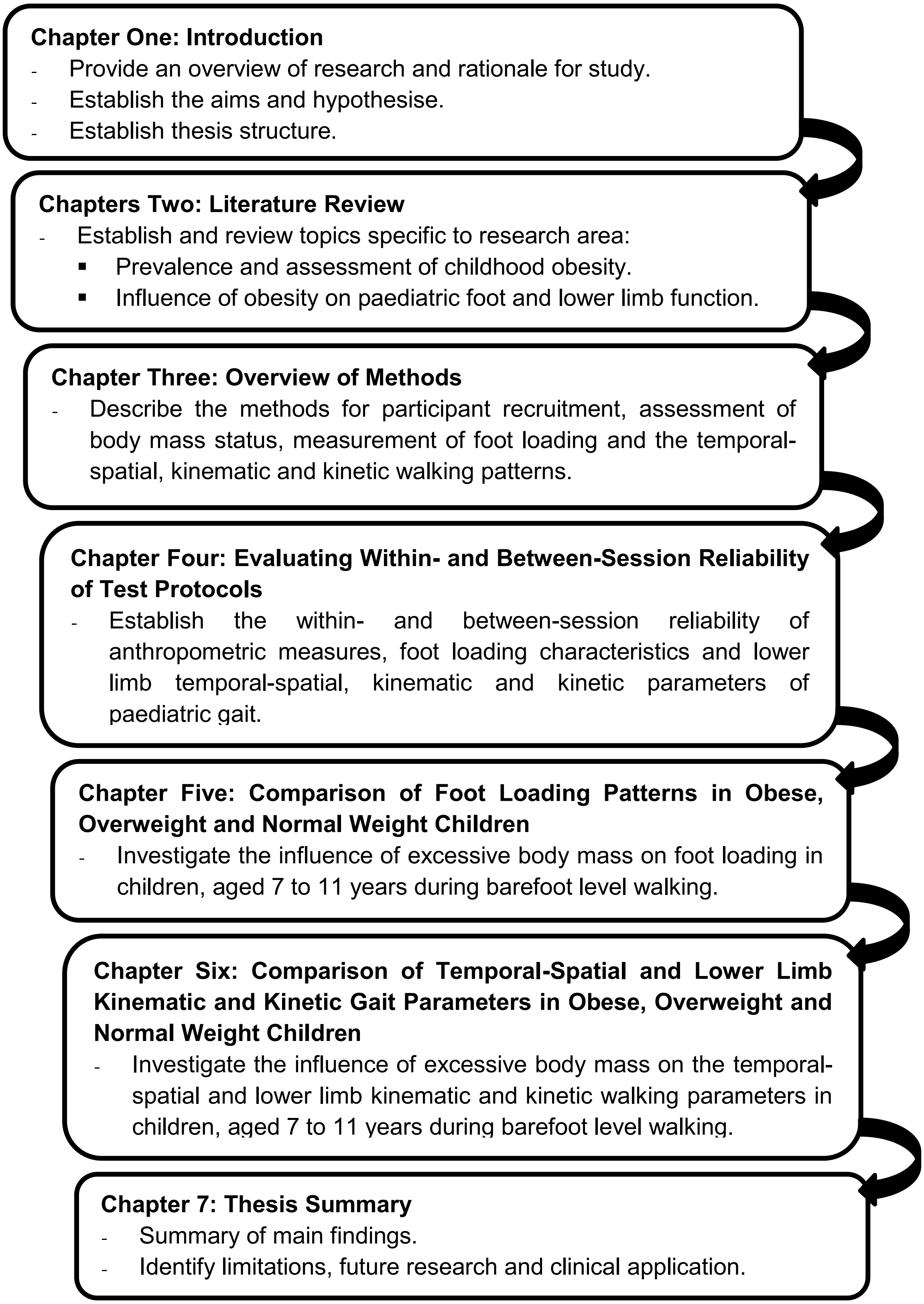
1.2 Aims and Hypotheses of the Study

The first aim of this work was to establish the within- and between-session reliability of anthropometric measures, planter foot loading and temporal-spatial, kinematic and kinetic lower limb walking parameters in a group of children, aged 7 to 11 years. It was hypothesised that the collection of reliable data was possible in children using BMI and skinfold measures, the MatScan® pressure platform (TekScan, USA) and VICON (VICON 612, Oxford, UK) motion analysis system respectively.

The second aim of this work was to determine the impact of overweight and obesity on the plantar foot loading characteristics in children, aged 7 to 11 years, during barefoot level walking. It was hypothesised that overweight and obese children would display increased levels of peak plantar pressure and force as well as increased normalised force across the plantar surface of the foot in comparison to normal weight children. It was also hypothesised that these children would display greater pressure-time and force-time integrals when compared to their normal weight peers.

Following this, the final aim of this work was to identify temporal-spatial, kinematic and kinetic alterations of the lower limb during walking in the identified population. First, it was hypothesised that overweight and obese children would demonstrate altered temporal-spatial gait characteristics as well as altered lower limb kinematic and kinetic walking patterns during gait. Secondly, it was hypothesised that a relationship would be found between plantar foot loading and the dynamic joint kinematics and kinetics of the lower limb in overweight and obese children.

Figure 1.1 outlines a summary of this thesis, providing an overview of the contents of each chapter whilst demonstrating the progression of this research project.



Chapter One: Introduction

- Provide an overview of research and rationale for study.
- Establish the aims and hypothesise.
- Establish thesis structure.

Chapters Two: Literature Review

- Establish and review topics specific to research area:
  - Prevalence and assessment of childhood obesity.
  - Influence of obesity on paediatric foot and lower limb function.

Chapter Three: Overview of Methods

- Describe the methods for participant recruitment, assessment of body mass status, measurement of foot loading and the temporal-spatial, kinematic and kinetic walking patterns.

Chapter Four: Evaluating Within- and Between-Session Reliability of Test Protocols

- Establish the within- and between-session reliability of anthropometric measures, foot loading characteristics and lower limb temporal-spatial, kinematic and kinetic parameters of paediatric gait.

Chapter Five: Comparison of Foot Loading Patterns in Obese, Overweight and Normal Weight Children

- Investigate the influence of excessive body mass on foot loading in children, aged 7 to 11 years during barefoot level walking.

Chapter Six: Comparison of Temporal-Spatial and Lower Limb Kinematic and Kinetic Gait Parameters in Obese, Overweight and Normal Weight Children

- Investigate the influence of excessive body mass on the temporal-spatial and lower limb kinematic and kinetic walking parameters in children, aged 7 to 11 years during barefoot level walking.

Chapter 7: Thesis Summary

- Summary of main findings.
- Identify limitations, future research and clinical application.

Figure 1.1. Thesis structure

CHAPTER TWO: LITERATURE REVIEW

The following chapter will review the definition and prevalence of childhood obesity. Current literature pertaining to the assessment of childhood obesity will be critically explored with a focus upon two commonly utilised methods, the body mass index and skinfold measurement. Literature presenting the musculoskeletal consequences of childhood obesity will be discussed, detailing its impact on foot structure, foot loading and lower limb biomechanical parameters of paediatric gait.

2.1 Childhood Obesity

2.1.1 Overview

Childhood obesity is recognised as a major public health concern and shows continued escalation (Lobstein et al. 2004). According to Schultz et al. (2011), childhood obesity is the most common chronic illness in western countries and is considered an epidemic. The World Health Organisation (2008) described the concern as, one of today's most visible, yet neglected public health problems. With the prevalence of childhood obesity increasing, there is need for early detection, prevention and treatment of the condition. However, childhood obesity is confounded by the fact that it is a difficult condition to define (Cole et al. 2000).

Obesity is defined as the accumulation of excessive body fat that presents a risk to health (World Health Organisation, 2008). However this definition is not suitable for children as there is no universally agreed criterion for the measurement of body fat and as a result no universally accepted definition for childhood obesity (McCarthy et al. 2006). Reilly et al. (1999) proposed a criterion based on body mass capable of defining an overweight child. Their criterion stated that a child should be defined as overweight when their BMI is greater than the 85th centile and obese when BMI exceeds the 95th centile for age and gender. Both Barlow and Dietz (1998) and Reilly et al. (1999)

proposed that when defining obesity in this way, children with a BMI above the 95th centile are likely to be excessively fat; however the authors did not propose what an excessive level of body fat actually was. In addition, factors such as physiological variations in body fat, varying growth and maturation rates, classification thresholds, gender and ethnicity also complicate the issue (Reilly, 2010).The problem of classifying childhood overweight and obesity is further highlighted by Reilly et al. (2010), in that definitions adopted across studies frequently vary, making comparisons difficult. The issues regarding the assessment of childhood obesity and the use of BMI in the weight classification of children is discussed further in section 2.2 (page 9).

2.1.2 Prevalence

In the past few decades the number of overweight and obese children has increased worldwide. In recent years, within the UK, the Health Survey for England (HSE) has provided the most robust source of trend data on childhood obesity (Dinsdale et al. 2011). Between 1995 and 2011, HSE data reported a steady rise of obesity prevalence for children aged 2-15 years of over 0.5% per year and among boys, aged 2 to 15 years, from 11% to 17%; with an equivalent increase for girls, from 12% to 16%. In 2011, statistics from the HSE highlighted that 31% of boys and 28% of girls, aged 2-15 years, were classified as either overweight or obese, with a BMI at or above the 85th and 95th BMI percentiles of the British 1990 growth reference population (Mandalia, 2012).

The National Child Measurement Programme (NCMP) has provided data since 2006 demonstrating trends in children’s weight. In this analysis, children with a BMI greater than or equal to the 85th and 95th percentile of the British 1990 growth reference BMI distributions were classified as overweight or obese respectively. In 2011-12 figures from the NCMP reported that from a sample of 1,056,780 children measured, overweight and obesity among 6-7 year old children was 13.1% and 9.5% respectively

(13.6% and 9.9% for boys and 12.5% and 9.0% for girls) and among 10-11 year olds was 14.7% and 19.2% respectively (14.7% and 20.7% for boys and14.7% and 17.7% for girls). The figures reported by the NCMP indicated that 28.3% of children in the UK, aged 6 to 11 years were classified as either overweight or obese (The Health and Social Care Information Centre, 2012).

The current obesity epidemic is particularly problematic amongst ethnic minority populations (Taylor et al. 2005). London and its surrounding boroughs have some of the highest reported levels of obesity in the UK and also have a high percentage of ethnic minority children within its schools (Greater London Authority, 2011; The Institute of Community Health Sciences, 2003). An understanding of the prevalence of overweight and obesity in these populations is important since some ethnic groups may be particularly vulnerable to the adverse health effects associated with obesity (The Institute of Community Health Sciences, 2003). Current statistics report that the prevalence of overweight and obesity among Black, Asian, Chinese and mixed race children, aged 6-11, living in London are 36.9%, 28.9%, 23.5% and 29.1% respectively (Greater London Authority, 2011).

The escalation of childhood obesity over the past two decades is of even greater concern when it is considered that 50% of obese children remain obese in adulthood and as a result are associated with increased adult mortality and morbidity (The Health and Social Care Information Centre, 2012). Thus, the accurate identification of the overweight and obese child in health related research for early intervention is of paramount importance.

2.2 Assessment of Childhood Obesity

2.2.1 Overview

Numerous tools and methods have been developed to assess obesity in children, ranging from advanced laboratory based approaches, such as hydrodensiometry, air displacement plethysmography (ADP), dual-energy x-ray absorptiometry (DEXA) and magnetic resonance imagery (MRI) to more traditional field based techniques, including body mass index (BMI), skinfold techniques and bioelectrical impedance analysis (BIA). A summary of the underlying principles and strengths and limitations of these techniques has been conducted in a number of reviews (Pietrobelli and Heymsfield, 2002; Pietrobelli and Tato, 2005; Wagner and Heyward, 1999; Wells, 2006) and as such is not within the scope of this literature review. The major focus of the following review is the use of BMI and skinfold measurement in the assessment of childhood obesity, as these methods are to be adopted in this research to classify body mass status and body fat % in children aged 7 to 11 years.

Currently there is no universally accepted definition for childhood obesity and as a result no definitive criterion measure for the assessment of childhood obesity has yet emerged. Since obesity itself, is by definition, excess body fatness (Reilly et al. 2000) it has been suggested that childhood obesity should be defined on the basis of a body fatness measurement (Reilly, 1998). However, age and gender related physiological variations in body fat can make it difficult to distinguish between normal and excessive adiposity in children (Reilly, 2010). It also appears that the classification of childhood obesity is limited by a lack of validation studies in children incorporating many of the tools commonly used to assess adiposity. Many highly acceptable or *“gold”* standard techniques, such as hydrodensiometry, DEXA and MRI scanning are not suitable for field based paediatric research for a number of reasons including cost, ethics, availability, radiation exposure, impracticality in epidemiological use and the reliance of children remaining still and cooperative for some length of time (Wells, 2006; Wells et al. 2006). In addition to these methods, there are anthropometric techniques, such as BMI and skinfolds, which are more commonly used within paediatric research. Due to the simplicity of these measures, it means large scale data collection can be performed, resulting in large amounts of reference data (McDowell et al. 2005). The attraction of using anthropometric to evaluate childhood obesity is appealing, provided they have the accuracy and precision required.

2.2.2 Body Mass Index

The BMI is a commonly used proxy measure of overweight and obesity, where body mass is adjusted for body stature (kg/m^2). It is calculated as: Body Mass (kg) / Stature $(m)^2$. The BMI is viewed as the most practical diagnostic measure for identifying obesity and levels of body weight due to its simplicity, low cost and non-invasive procedure (Abbott et al. 2002; Barlow and Dietz, 1998).

One major advantage to the use of BMI is the practicality of the measure, relating to the fact that it is quick to perform, easy to calculate, non-invasive, offers little or no risk to the subject, involves minimal expertise and equipment and is essentially cost free. Reilly et al. (2010) described the measure as inexpensive and valid enough to be practical in most clinical and public health settings. Reilly (2010) also described the measure as the optimal means for defining obesity in children and adolescents, with advantages that outweigh its limitations. It has also been deemed suitable for screening children in epidemiological research (Must and Anderson, 2006).

While BMI is recognised internationally as an established measure of overweight and obesity in adults, its validity in use with children is inconclusive. A cut-off point of 25 kg/m^2 and 30 kg/m^2 is recognised as a definition for adult overweight and obesity respectively (WHO, 2008). Fixed threshold such as these are suitable to grade overweight and obesity in adults as their BMI has been shown to change relatively slowly with age (Garrow and Webster, 1985). In contrast, a child's BMI changes considerably as they mature, rising steeply in infancy, falling during pre-school years and then rising again into adulthood (Power et al. 1997). Consequently, because a child's BMI changes significantly between birth and adulthood, fixed thresholds, such as those described for adults, should not be applied to children as they may provide misleading findings (Dinsdale et al. 2011). Additionally, the relationships between BMI, fat mass and fat-free mass are further complicated by varying growth and maturation rates in children (Maynard et al. 2001; Miller et al. 2004). Growth leads to marked changes in body composition, including alterations in the relative proportions of water, muscle, fat and bone (Castilho et al. 2008). Also, the patterns of growth differ between boys and girls; as a result, Castilho et al. (2008) proposed that changes in body composition will vary between genders due to variations in peak growth rates. Therefore, instead of using fixed BMI values to classify a child's BMI, it has been proposed that children's BMI be classified using thresholds, derived from a reference population, that take into account the child's age and gender (Cole et al. 2000).

In the UK, the British 1990 growth reference standards are recommended for population monitoring and clinical assessment in children aged 4 years and over (Dinsdale et al. 2011). The British 1990 growth reference provides centile curves for children from birth to 23 years and is based on a sample of 32,222 measurements collected between 1978 and 1994 (Cole et al. 1995). Dinsdale et al. (2011) proposed that for population monitoring an overweight child is to be defined as that with a BMI ≥ 85th percentile and an obese child as that with a BMI ≥ 95th percentile whereas McCarthy et al. (2003) defined overweight and obesity in children as a BMI in excess of the 91st and 98th percentiles respectively. In contrast Mast et al. (2002) defined a child as having a BMI greater than the 90th percentile as being overweight, whereas the obese child is that with a BMI greater than the 97th percentile.

Another approach based on BMI, proposed by the International Obesity Task Force (IOTF) is to use the childhood *"equivalents"* of the BMI in adults, which are derived to match the adult BMI thresholds for overweight (25 kg/m^2) and obesity (30 kg/m^2) (Cole et al. 2000). Jebb and Prentice (2001) urged the use of the IOTF proposed reference standards for obesity in children; however Reilly et al. (2000) reported that when screening for childhood obesity, the recommendations based upon the IOTF approach were associated with lower sensitivity in both boys and girls in comparison to the obesity definition based upon BMI ≥ 95th percentile relative to the British 1990 growth reference standards. This was supported by Fu et al. (2003) who also reported that the IOTF recommended BMI cut-off values had low sensitivity and may underestimate the prevalence of childhood obesity in comparison to population specific measures.

Early work in children identified a relationship between BMI and total body fatness (Deurenberg et al. 1991; Roche et al. 1981) with these results highly specific for children with the greatest amount of body fat (Himes and Bouchard, 1989; Marshall et al. 1990). Pietrobelli et al. (1998) performed a validation study of BMI as a measure of adiposity in children and adolescents, aged 4-19 years. The authors reported a strong relationship in boys and girls (r^2 = 0.79-0.83) between BMI and percentage body fat as measured by DEXA. However, wide confidence limits on the BMI-body fat relationship were also reported in this study, with individuals of similar BMI having large differences in their percentage body fat. These results indicated that BMI is primarily a measure of size and not strictly body composition and BMI may not be directly proportional to percentage body fat (Abbott et al. 2002).

More recently, Neovius et al. (2005) concluded that BMI demonstrated *"high validity"* for detecting level of body fat in children and adolescents, as attested by the strong correlation between BMI and percentage body fat measured by ADP, in a sample of 474 healthy adolescents (r^2 = 0.68-0.73, $p<0.01$). Similarly, Steinberger et al. (2005)

reported that in a cohort of 11-17 year old adolescents (N = 130), BMI was highly correlated with DEXA measures of percentage body fat (r^2 = 0.85, p<0.01) and fat mass (r^2 = 0.95, p<0.01). The validity of the BMI as a method for estimating body fat in children has been further reaffirmed, as attested by its significant positive correlation to other criterion measures of body fat, such as BIA (r^2 = 0.92, p<0.01) in a sample of 228 six-year-old children (Pecoraro et al. 2003), ultrasound (r^2 = 0.50-0.73, p<0.05) in both an obese (N = 51, 11.5 ± 2.6 years) and control group (N = 33, 12.2 ± 2.7 years) of children (Semiz et a. 2007) and isotope dilution (r^2 = 0.68, p<0.05) in a study of 109 children, aged 6-10 years (Abbott et al. 2002).

With respect to reliability of the BMI, Taylor et al. (2002) reported a coefficient of variation of <1% for the measure in children, indicating minimal variability between trials (Portney and Watkins, 2000). Taylor et al. (2002) also reported minimal intra- and inter-tester variability when measuring the BMI of children. Furthermore, Stoddard et al. (2008) reported *"good"* absolute mean difference reliability for height (0.30 ± 0.24cm) and weight (0.02 ± 0.04kg) used to determine BMI in a sample of 4-12 year-old children (N = 70). More recently Berkson et al. (2013) reported excellent intra- and inter-rater reliability of BMI measures for category classifications in a cohort of 7-13 year-old children (N = 120) as attested by high intra-class correlation coefficients (0.96-0.99) and minimal absolute mean differences for both height (0.37 ± 0.91cm) and weight (0.03 ± 0.09kg). Similarly, Oza-Franks et al. (2012) also reported BMI category classifications showed *"substantial"* reliability (Kappa statistics: 0.94-0.96) and minimal mean differences (95% confidence intervals) of 0.45cm (0.41-0.48) for height, 0.07kg (-0.01-0.15) for weight and 1.37kg/m^2 (1.20-1.53) for BMI respectively in a sample of 1189 children (8.6 ± 0.6 years). The authors also reported high BMI sensitivity (proportion of children with a high BMI, who were correctly recorded as having a high BMI) and specificity (proportion of children who did not have a high BMI, who were correctly identified as not having a high BMI) in correctly identifying overweight (97-

99%) and obese (96-99%) children respectively. The results concur with earlier work from Neovius et al. (2004) where BMI also demonstrated both high sensitivity (92%) and high specificity (92%) in determining excess adiposity in adolescents (N = 474).

Although there is growing evidence to support BMI as a measure of adiposity in children (Freedman and Sherry, 2009), there are several limitations to its use. BMI naturally increases through childhood and adolescence, primarily because of increases in fat-free mass content during maturation (Haroun et al. 2005; Maynard et al. 2001; Wells et al. 2002). Therefore it can easily be misinterpreted that alterations in BMI are as a result of changes in fat mass, when it may be attributed to fat-free mass. This is supported by Frakenfield et al. (2001) who stated that the BMI does not identify individuals solely on their body fat mass. As a result, the likelihood of incorrectly identifying a healthy subject with increased muscle bulk as obese would be increased, reducing the specificity of this measure. Freedman et al. (2005) and Taylor et al. (2002) suggested that the accuracy of the BMI varies with the degree of fatness in children, with the measurement performing better in children with greater levels of adiposity. The BMI therefore appears highly sensitive for obesity; however the specificity of this measure may be reduced.

Daniels et al. (1997) stated that when BMI is used as a measure of body fatness in children, it is important to consider the maturation stage, gender and ethnicity in the interpretation of the results. Deurenberg and Deurenberg-Yap (2001) reported that the relationships between BMI and body composition differ across different ethnic groups. Ellis and colleagues (1997) indicated that the relationship between percentage body fat and weight and height, corrected for age in young males (N = 297) and females (N = 313) aged 3-18 years, differed between Hispanic (N = 142), African American (N = 182) and white (N = 286) ethnic groups (Ellis, 1997 and Ellis et al. 1997). Deurenberg et al. (1998) also reported clear differences between ethnic groups in terms of their

BMI-percentage body fat relationship. This has led to the debate as to whether ethnic-specific BMI age-related reference standards (as described previously) be used to diagnose childhood overweight and obesity or indeed whether population specific reference standards should be used across each country (Misra, 2003). A study by Taylor et al. (2005) examining the obesity status among a representative sample of children and adolescents from different ethnic groups in East London found no significant differences in BMI or in the prevalence of overweight and obesity across all ethnic groups. Stevens (2003) and Viner et al. (2010) also argued that ethnic specific revisions of body mass index cut-offs to define overweight and obesity are not warranted; however, there is currently a lack of consensus regarding this issue, the development of which is ongoing and warrants further investigation.

Barlow and Dietz (1998) proposed a standard deviation score (z-score) be used to define childhood obesity both for clinical practice and epidemiology. A standard deviation or z-score for BMI is a measure of the number of standard deviations from the expected mean BMI for an individual and enables standardisation for age and gender (Dinsdale et al. 2011). Barlow and Dietz (1998) proposed a BMI z-score of greater than the 85th percentile as being overweight (BMI z-score ≥ 1.04) and greater than the 95th percentile as being obese (BMI z-score ≥ 1.64). In a validation study comparing classification indices, Mei et al. (2002) supported the use of BMI z-scores in classifying both underweight and overweight children aged 3-19 years (N = 11096) as attested by the high correlation coefficients with DEXA measurements of percentage body fat ($r^2 = 0.71\text{-}0.88$) and total fat mass ($r^2 = 0.65\text{-}0.87$). The authors reported that in addition to removing the influence of age and gender, the use of BMI z-scores offers a simple, low-cost approach to assessing body fatness in children.

More recently the validity of BMI z-scores has been assessed in a sample of Australian white Caucasian (N = 96) and Australian Sri Lankan (N = 42) children (9.4 ± 2.7 years) by Wickramasinghee et al. (2005). Following measurement of total body water and fat-mass through isotope dilution techniques, the authors reported a significant positive correlation between percentage body fat and fat-mass in both the Caucasian ($r^2 = 0.48$ and 0.61, $p<0.01$) and Sri Lankan ($r^2 = 0.64$ and 0.73, $p<0.01$) children respectively. The authors also reported that BMI z-scores had high predictive value (66-100%) in correctly identifying overweight and obese children. Cole et al. (2005) also reported BMI z-scores to be the optimal BMI measure for assessing adiposity on a single occasion in growing children. Furthermore, Bell et al. (2007) reported that children aged between 6-13 years (N = 177) with a higher BMI z-score (>2.00 standard deviation) indicative of childhood obesity, reported increased cases of musculoskeletal pain, headaches, anxiety and depression. The authors stated that BMI z-scores are extremely practical in classifying overweight and obesity in childhood and as such could be used as a screening tool for many medical complications and most co-morbidity associated with obesity. This criteria for defining childhood obesity is widely supported in the scientific literature (Bell et al. 2007; Bundred et al. 2001; Dietz and Robertson, 1998; Dinsdale et al. 2011; Haroun et al. 2005; Must and Anderson, 2006; Reilly, 2010; Reilly et al. 2010; Wells et al. 2006), has been adopted in the UK by the NCMP and as such will be used in this research to classify overweight and obesity in children.

BMI for the assessment of obesity in children is practical, risk free, cheap and feasible. It is however important to appreciate the limitations associated with this measure and that the criteria used to define obesity are supported in the most recent scientific literature. It has also been suggested that BMI be supplemented with other simple anthropometric measures to more accurately define a child’s obesity status, such as skinfold measurements (Pietrobelli et al. 2003).

2.2.3 Skinfold Measurements

Measurement of skinfold thickness is an anthropometric technique where subcutaneous fat can be estimated (Himes, 2009). Due to its relative low cost and practical ease and speed, skinfold measurement has a long history of use as an indicator of body fatness (Wagner and Heywood, 1999). Skinfold thickness can be measured all over the body, although the sites most often used are the arms (biceps and triceps), under the scapula (subscapular) and above the iliac crest (supra-iliac) (Pietrobelli and Heymsfield, 2002). Increasing the number of measurements sites has been shown to improve the sensitivity and specificity of this technique in estimating fat mass (de Onis et al. 2004). When such measurements are chosen, it has been advocated that the technique involves pinching the skinfold with the thumb and forefinger, pulling it away from the underlying tissue and placing the callipers on the fold (de Onis et al. 2004; Marfell-Jones et al. 2007). The skinfold calliper measures the thickness of the skinfold and the underlying layer of subcutaneous fat. This measurement technique is however based on the assumption that (1) skinfold thickness is a good indicator of subcutaneous fat and (2) that there is a good relationship between subcutaneous fat and total body fat (Wagner and Heywood, 1999). Lohman (1981) reported that the total error of estimate of percentage body fat from skinfold thickness measurements was 3.3%. Later work from the same author reported similar findings, with standard error of estimation to be 3.5% for percentage body fat determined from skinfold measurement (Lohman, 1992).

Although there is debate with regards to the accuracy of the skinfold measurements, the use of this technique is common in adult studies and has been highly correlated with total body fat in children in comparison to criterion measures such as DEXA, BIA, isotope dilution and ADP (Freedman et al. 2007; Michels et al. 2012; Nasreddine et al. 2012; Watts et al. 2006). It has also been reported that skinfold measurements have high specificity in detecting excess adiposity in children (Bedogni et al. 2003; Sarria et al. 2001) and that fat mass measurements using skinfold thickness are comparable across different BMI ranges (Pecoraro et al. 2003).

Early work from De Lorenzo et al. (1998) found no significant difference between percentage body fat values derived from DEXA and skinfold measures in adolescents (N = 26). Similarly, Watts et al. (2006) reported strong relationships ($p<0.01$) between percentage body fat derived from skinfold and DEXA measurements ($r^2 = 0.79$) in 38 obese children (12.7 ± 2.1 years). Freedman et al. (2007) established that skinfold thickness at the triceps and subscapular, measured in 1196 children aged 5-18 years, were significantly correlated with percentage body fat ($r^2 = 0.81$-0.90, $p<0.001$) as measured by DEXA. However the authors did note that the ability to predict total body fat from skinfold thickness measurements reduced in overweight children. More recent work comparing fat mass in children, aged 5-11 years (N = 480) reported significant moderate-to-good correlations between percentage body fat as determined by triceps and subscapular skinfold measures ($r^2 = 0.64$-0.77, $p<0.01$) in comparison to ADP (Michels et al. 2012). In support of these findings, Nasreddine et al. (2012) also reported excellent correlations ($r^2 = 0.76$-0.91, $p<0.05$) in percentage body fat measures derived from skinfold based estimates in comparison to isotope dilution techniques in a cohort of 158 children, aged 8-10 years. The authors concluded that the use of skinfold measure as markers of body fat in children is warranted where *"gold standard"* measures are either not available or feasible.

Semiz et al. (2007) identified several factors that affect the validity and reliability of skinfold measurement. The authors stated that the measurements of skinfolds are sensitive to intra- and inter-tester variability due to the selection of the site for skinfold thickness (which is often dependent upon identifying the correct location of anatomical landmarks), the variation in pinching the skin and the variation in the application and recording of the callipers. Semiz et al. (2007) discussed the practicality of obtaining valid and reliable measurements in obese subjects, as it seems reasonable to hypothesise that with greater amounts of subcutaneous skin, skinfold measurements on obese subjects will be associated with higher variability. To help try and reduce these potential sources of error and standardise skinfold measurements, guidelines for the anatomical location of the skinfold sites and measurement technique has been published by the International Society for the Advancement of Kinanthropometry (Marfell-Jones et al. 2007) and the World Health Organisation Growth Reference Study Group (de Onis et al. 2004). Both de Onis et al. (2004) and Marfell-Jones et al. (2007) indicated that repeatability of skinfold measurement can be strengthened with attention to detail and well-trained operators.

In regards to the reliability of skinfold measurement; de Onis et al. (2004) assessed the technical error of measurement (TEM) associated with their precision. The TEM assesses differences between repeat measurements taken by the same person on the same subject both within- and between-testing sessions (intra-rater variability) or by at least two researchers taking the same measurement on the same child (inter-rater variability). The same authors proposed that a TEM of 5% is the maximum allowed difference for acceptable precision used across studies; this equates to 2.0mm for skinfold measurements (de Onis et al. 2004). Work from the World Health Organisation Growth Reference Study Group (2006) assessed the TEM and reliability of triceps and subscapular skinfold measurements in children, aged 2-5 years (N = 8500), across six countries. The study reported intra- and inter-rater TEM between 0.29-0.61mm and 0.36-0.87mm respectively. Inter-rater reliability assessed using coefficients of reliability for repeated measures of skinfold thickness, reported values ranging from 0.75-0.92, indicating that 75-92% of the total variability is true variation whilst the remaining 8-25% is attributable to measurement error.

More recent work investigating the intra- and inter-rater variability and reliability of anthropometric measurements in children, aged 2-9 years (N = 16224) across eight countries, reported acceptable intra- and inter-rater agreement for skinfold measures at the triceps, biceps, subscapular and suprailliac (Stomfai et al. 2011). The authors reported intra-rater TEM between 0.12-0.47mm and an intra-rater reliability (assessed via coefficients of reliability) of 97.7%. Inter-rater TEMs were between 0.13-0.97mm and inter-rater agreement for repeated measurements were above 88%. The authors also reported that differences in reliability in relation to obesity were not present, with TEM values lower and coefficient of reliability higher in obese children in comparison to their non-obese counterparts. The reliability of skinfold measurements is further supported in a number of studies in both adolescent (Nagy et al. 2008) and child (Franier et al. 2007; Yeung and Hui, 2010) populations where intra- and inter-rater TEMs were smaller than 1mm in measurements taken at the triceps, biceps, subscapular, suprailliac, thigh and calf respectively. In all cases intra- and inter-rater coefficients of reliability were greater than 90%.

The thickness of skinfold measurement from different sites on the body can be used as raw values to give an indication of subcutaneous adipose tissue or they can be summed and incorporated into prediction equations to estimate total body fat. Many equations exist for the estimation of body fatness from skinfold measurement in children. De Lorenzo et al. (1998) and Dezenberg et al. (1999) indicated that many of the multiple regression equations resulted in the over estimation of body fat levels in children. This can be largely attributed to three main limitations: (1) lack of cross validation for the equations of children of varying maturation and size, (2) individual variation in fat proportion and (3) changes in the chemical composition of body density that occurs through puberty (De Lorenzo et al. 1998; Dezenberg et al. 1999; Janz et al. 1993).

Slaughter et al. (1988) attempted to account for these limitations, taking into account gender, ethnicity and pubertal status by using a large heterogeneous paediatric population (500 boys and 116 girls, mean age 9.9 years) and deriving multi-component equations utilising measures of body density, total body water and bone mineral content that would observe changes in fat free mass composition. The validity of the Slaughter et al. equations has been established in a number of scientific papers and these are effectively the *"standard"* equations used in North America and the UK (Himes, 2009; Reilly et al. 2010). Lohman (1989) stated that the Slaughter et al. equations overcame excessive estimation of total body fat, as they accounted for the varied chemical composition of childhood fat free mass. Steinberger et al. (2005) reported *"high"* correlations between the Slaughter et al. equations, percentage body fat and total fat mass, as measured by DEXA, in a cohort of 130 adolescents, aged 11-17 years ($r^2 = 0.91$-0.93, $p<0.01$). The authors also reported that the correlations were similar in *"heavy"* and *"thin"* children respectively ($r^2 = 0.89$ and 0.79, $p<0.05$). More recently, Nasreddine et al. (2012) demonstrated high correlations between percentage body fat as estimated by the equations of Slaughter et al. in comparison to isotope dilution techniques ($r^2 = 0.78$-0.89, $p<0.05$). In addition, Michels et al. (2012) reported that body fat and fat mass percentage estimates derived from the Slaughter et al. equations correlated more highly with ADP ($r^2 = 0.71$-0.80, $p<0.01$) in comparison to other published equations used in the assessment of body composition in children (Deurenberg et al. 1990; Deurenberg et al. 1991; Dezenberg et al. 1999; Goran et al. 1996; Schaefer et al. 1994; Susan et al. 2004; Tyrrell et al. 2001).

Skinfold measurement is another practical method for the initial assessment of obesity in children. As with BMI, it is important to take into consideration the limitations associated with this measure, particularly in the selection of prediction equations used to estimate body fatness in children. However, when used in addition to BMI, skinfold measurements can substantially improve the estimation of body fatness in children and adolescents (Freedman et al. 2007) and as such will be utilised alongside BMI-SDS values in this research to assess adiposity levels in children.

2.3 Musculoskeletal Consequences of Childhood Obesity

2.3.1 Overview

Childhood obesity leads to multiple co-morbidities affecting multiple body systems and various musculoskeletal disorders, affecting the lower limb and feet (Hills et al. 2002; Must and Strauss, 1999). Childhood obesity is thought to prevent normal movement patterns and predispose children to musculoskeletal pain and injury (Wearing et al. 2006). Persistent and abnormal loading of the musculoskeletal system has been implicated in the pre-disposition to pathological gait patterns (Shultz et al. 2011), loss of mobility (Messier et al. 1994) and to a range of long-term orthopaedic conditions including Blount's Disease (Dietz, 1998) and Slipped Capital Epiphysis (Murray and Wilson, 2008; Wabitsch et al. 2012). Nevertheless, the implications of childhood obesity on the lower limb musculoskeletal and locomotor systems, particularly during weight bearing tasks are poorly understood (Krul et al. 2009; de Sa Pinto et al. 2006).

Previous research has revealed differences in plantar loading (Dowling et al. 2004; Mickle et al. 2006), foot structure (Riddiford-Harland et al. 2011), mechanics of foot loading (Messier et al. 1994), gait characteristics (Schultz et al. 2009) and muscular strength and power (Riddiford-Harland, 2006) when comparing obese with non-obese children. Other short-term problems commonly cited among obese children include general discomfort in simple activities such as walking and stair climbing (Hills et al. 2002) and pain in the joints of the lower extremity (Stovitz et al. 2008; Tanamas et al. 2011). Hills et al. (2002) commented that these pathologies may be due to the increased stresses placed upon the feet and the greater absolute loads experienced at these joints by the excessive mass. A greater understanding of these areas will have implications for the prevention, treatment and management of pathological gait patterns, loss of mobility and other mal-adaptations in the lower extremities of obese children. The remainder of this chapter will discuss current literature detailing the impact of obesity on the musculoskeletal structure and function of the paediatric foot and lower limb. In particular, this review will focus on the influence of childhood obesity on foot structure, plantar loading and gait mechanics and will also detail the musculoskeletal disorders associated with obesity.

2.3.2 The Paediatric Foot

The feet, as the bodies' base of support, are subjected to changing patterns of stress as they continually withstand ground reaction forces during common 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 of children (Hills et al. 2002; Wearing et al. 2006). The following sections will review current literature pertaining to the assessment of foot loading in children, the development of the paediatric foot and the reliability of plantar pressure assessment. Following which, literature detailing the influence of childhood obesity on paediatric foot structure and dynamic foot function will be critically explored.

2.3.2.1 Analysis of Foot Loading

Plantar pressure assessment is commonly used in the clinical evaluation of the foot and provides insight into the plantar loading characteristics during functional activities such as walking and running (Orlin and McPoil, 2000). Plantar pressure assessments can determine loading characteristics on specific plantar regions of the foot (Rosenbaum and Becker, 1997). Several authors have commented upon the usefulness of plantar pressure assessment in characterising clinical problems of the foot (Cavanagh and Ulbrecht, 1994; Hennig, 2002). When compared to other assessment devices, pressure measurement systems are easier to implement and use, less time consuming and cumbersome to participants, less expensive than complex gait analysis equipment such as force platforms and measurements are easily acquired, processed and interpreted (Giacomozzi, 2011).

There are numerous commercially available systems used to assess plantar pressures, commonly found in two different formats: an in-shoe or platform based system. The validity and reliability of numerous systems has been documented throughout the literature suggesting they are able to accurately quantify dynamic plantar loading patterns (Cousins et al. 2012; Giacomozzi et al 2010: Gurney et al. 2008; Zammit et al. 2010). Giacomozzi (2011) recently recommended the use of platform based systems in comparison to in-shoe systems as they allow the collection of data in a barefoot state, removing the influence of footwear, which can mask high pressures. Additionally, the entire foot/ground contact is captured and the participants have no wires or data boxes attached to them which may influence their gait.

Plantar pressure assessment has been used to evaluate the foot loading characteristics of typically developing children (Alvarez et al. 2008) and has advanced our understanding of the loading on the foot during developmental stages (Bosch et al. 2009) and to evaluate altered characteristics of foot function in disease specific populations (Yan et al. 2013). However, as yet, no study has presented data for the foot loading characteristics of obese, overweight and normal weight children, during barefoot walking, across multiple regions of the foot, conforming to the guidelines for the standard units of measurement currently recommended by the International Foot and Ankle Biomechanics Community (i-FAB) in relation to the presentation of foot pressure measurement variables.

2.3.2.2 Reliability of Foot Loading

There are numerous commercially available systems currently employed by clinicians and researchers alike to assess plantar loading (Giacomozzi, 2010). The reliability of equipment commonly used for methods of plantar pressure assessment has been established in a normal population of adults (Hughes et al. 1991; Gurney et al. 2008; Zammit et al. 2010), however subsequent work using a paediatric population is lacking.

Early work by Hughes et al. (1991) assessing the reliability of plantar pressure measurements using the EMED F system®, reported that coefficients of reliability calculated for 1-25 trials showed a good level of reliability was achieved in ten adults, for force and pressure variables, across twelve regions of the foot (r^2 = 0.72-0.99). It was also demonstrated that the reliability of all measurements increased with the number of trials analysed. Hughes et al. (1991) also reported measurements related to time were more variable than the peak measures of force and pressure.

Recently, Gurney et al. (2008) conducted a study looking at the between-session reliability of plantar pressure measurement in an adult population using the EMED AT® system. Nine adults were recruited into this study and the reliability of peak pressure, maximum force, impulse and contact time were investigated across 10 regions of the foot using intraclass correlation coefficients (ICCs) and coefficients of variation (CoV). The results of this investigation showed the collection of reliable plantar pressure measurements were possible in a normal population of adults, the quality of which dependant on the region of the foot. Areas with typically high loading characteristics (medial and lateral hindfoot, lateral midfoot, medial and central forefoot, hallux and 2nd toe) demonstrated a higher level of reliability (ICCs: 0.76-0.96 and CoV: 5.5-17.7%) when compared to areas with lesser loading, in this instance the medial midfoot, lateral forefoot and lateral toes (ICCs: 0.68-0.80 and CoV: 16.9-30.9%).

This work is in agreement with that of Zammit et al. (2010) who also reported moderate-to-good within- (ICCs: 0.65-0.98 and CoV: 3.4-31.7%) and between-session (ICCs: 0.51-0.92 and CoV: 5.1-21.5%) reliability, in thirty healthy adults, for maximum force and peak pressure through seven regions of the foot, during barefoot level walking, using the TekScan MatScan® system. It was also reported that the midfoot and lesser toe regions demonstrated the greatest percentage difference both within- and between-testing sessions. Additionally, both maximum force and peak pressure in the lesser toe region exhibited a significant mean difference ($p<0.05$) between-sessions.

Whilst the work of the previously mentioned authors is of interest, it is important to acknowledge that the direct extrapolation of this work to the paediatric population may be invalid. It is commonly recognised in clinical practice that children's gait is associated with increased variability and therefore it is necessary to establish the feasibility of repeatable plantar pressure measurement in this population as, to the author's knowledge, the value of this clinical assessment is as yet undetermined.

2.3.2.3 Development of the Paediatric Foot

It is well known that the foot progresses through different changes to its structure and function during childhood (Bosch et al. 2007). The typical development of a child's foot is characterised by relevant changes to foot structure and foot function and is influenced by the age at which a child stands and starts walking (Bertsch et al. 2004).

Children's feet demonstrate typical differences in-comparison to the feet of adults. Instead of a medial gap, caused by the longitudinal arch, a characteristic fat pad can be found on the medial margin of the midfoot which serves to protect the paediatric foot from overloading. During the first 4-5 years of life, the fat pad shifts to the hindfoot and its primary function of shock absorption under the midfoot diminishes. Additionally, the longitudinal arch of the foot is thought to continue to develop until the age of 6-years (Hennig et al. 1994).

Functional changes to the paediatric foot have also been shown to occur with growth and aging. Bosch et al. (2007) investigated normative values of foot loading in 90 healthy children, aged 1-4 years, using the EMED pressure distribution platform. The authors reported that foot loading during the first years of independent walking is characterised by low plantar pressures, a high midfoot contact area and a low arch height. Additionally, Hennig and colleagues (1991, 1994) reported relative loads at the midfoot were three-times higher in infants in comparison to adults but generally reduced peak pressures were reported under the rest of the foot (Hennig and Rosenbaum, 1991; Hennig et al. 1994).

Bosch et al. (2009) analysing age-dependant pressure patterns in toddlers (1.3 ± 0.4 years), 7-year old children (7.0 ± 0.5 years), adults (31.9 ± 2.1 years) and seniors (68.7 ± 3.2 years) reported lower plantar pressures in toddlers (145.09 ± 33.8 kPa), higher values in 7-year old children (402.12 ±117.55 kPa) and adults (611.06 ± 226.20 kPa) and even higher values in seniors (800.42 ± 217.10 kPa). More recently in a longitudinal investigation of plantar pressure patterns, Bosch et al. (2010) revealed an increase in peak pressures at the hindfoot, midfoot, forefoot, hallux and toes in 36 healthy children from the age of 1-9 years.

Normative pressure data has been published by Alvarez et al. (2008) who identified age-related differences in plantar pressure profiles in a sample of 146 children ranging from 1.6-14.9 years. They reported that comparable foot pressure profiles could be identified across the age groups which were: (i) children under the age of two years; (ii) children aged two – five years and (iii) children older than five years. This work is interesting because it suggests the loading characteristics of children over five years are consistent.

It has been acknowledged that by the ages of 6-7 years the major structural changes to the medial-longitudinal arch have been completed in the child's foot, giving it a similar appearance to that of an adult's foot (Hennig and Rosenbaum, 1991; Hennig et al. 1994); yet changes in the foot loading characteristics continue with aging. However, it is widely accepted that a shift in peak pressures from the hallux to the hindfoot, accompanied by a continual increase in peak pressures at the forefoot are indicative of progression towards an adult-like foot loading patterns, usually reported in children between the ages of 7-9 years (Bosch et al. 2009; Bosch et al. 2010).

2.3.2.4 Foot Structure and Childhood Obesity

Throughout stages of growth and development the structure of the foot adapts in response to the demands placed upon it, with the paediatric foot particularly susceptible to deformity due to its distal location, flexibility and late(r) ossification (LeVeau and Bernhardt, 1984). Due to increased mechanical loading of the feet caused by excessive mass, it would appear reasonable to hypothesise that obesity may predispose children to musculoskeletal problems. A common musculoskeletal co-morbidity associated with childhood obesity is Pes Planus (flat feet) (Bordin et al. 2001; Chen et al. 2011; Pfeiffer et al. 2006; Villarroya et al. 2009). Pes Planus is a condition of the foot in which the medial-longitudinal arch (MLA) is lowered (Kim and Weinstein, 2000). The link between the development of pes planus and obesity is yet to be elucidated but is thought to be as a result of excessive body mass disrupting the immature musculoskeletal structure of the paediatric foot and consequently altering foot function (Dowling et al. 2001; Mickle et al. 2006; Mauch et al. 2008; Morrison et al. 2007).

The view that the structure of the child's foot is affected by obesity emerged from early studies utilising indirect measures of arch height (static footprint assessments), to characterise the weight bearing foot and also to identify the contact area of the midfoot;

the view being that the greater midfoot contact the more planus (flatter) the foot type. Mathieson et al. (1999) reported that the rationale behind capturing static footprint measures was based on the theory that the footprint responds to variations in the structure of the MLA and identifies relationships regarding dynamic function.

Riddiford-Harland et al. (2000) conducted the first work examining the effects of obesity on foot structure in prepubescent children. The authors utilised the footprint angle (FA) and Chippaux-Smirak Index (CSI) to characterise the foot structure of 62 obese and 62 non-obese children (mean age 8.5 ± 0.5 years). The authors reported a significant reduction in FA and significantly greater CSI scores in both the left and right feet of the obese children ($p<0.0001$). A decreased FA and an increased CSI are characteristics of structural foot change, such as a lowered MLA, a flatter cavity and a broader midfoot contact area; all of which have been associated with compromised foot function (Dowling et al. 2001). From these results, Riddiford-Harland et al. (2000) concluded that the lower MLA, as seen in obese children, appeared to be associated with a decrease in the integrity of the foot as a weight bearing structure.

Following up on the work of Riddiford-Harland et al. (2000); Dowling et al. (2001) utilised both static (FA, CSI) and dynamic (plantar pressures) measures to evaluate the impact of obesity on foot structure in prepubescent children. A smaller sample size was recruited in this study (N = 13 obese children and N = 13 non-obese children) yet similar findings emerged, with the obese children demonstrating a flatter foot type, confirming that obese pre-pubescent children appear to display changes in the structure of their feet. Changes in the foot structure of obese children, identified by indices of footprint analysis, which reflected a lower MLA, greater contact area or *“flatter”* foot type have also been reported in more recent studies (Chen et al. 2011; Mickle et al. 2006; Riddiford-Harland et al. 2011; Villarroya et al. 2009).

Unfortunately, current studies examining the effects of obesity of the structure of children’s feet have been limited in terms of subject number and age range. They also focussed on single foot dimensions, mostly plantar measures, which do not allow a comprehensive three-dimensional (3D) approach to classifying foot shape (Mauch et al. 2008). Mathieson and colleagues (1999, 2004) also suggested that the CSI was not a valid indicator of foot structure and the FA was an unreliable measure for footprint analysis. Further to this, Mathieson et al. (2004) suggested that such measures are of limited ability in the classification of foot morphology. In addition, Evans (2011) argued that the definition of flat foot is not standardised, making it a difficult condition to classify based upon indirect measures of arch height. Finally, to this author’s knowledge, there are no studies, which examine the influence of being overweight on foot structure; previous research has often combined overweight and obese groups and/or used the definition interchangeably. This work is important because differentiation between obese and overweight is required, particularly as current management strategies are looking at earlier intervention and preventing co-morbidities before children are obese.

This collection of work appears to support the view that that childhood obesity affects the structure of the paediatric foot and that children as young as 8-years of age display structural foot characteristics which may place greater strain on the soft-tissue and joint structures of the paediatric foot and as such raise the potential for musculoskeletal injury (Wearing et al. 2006). However, the conclusions from this body of work are limited as the validity of employing static footprint parameters as indirect estimates of arch height is a controversial topic, as the classification of foot structure via two-dimensional footprint analysis has been debated for decades in the medical and allied health fields, with the methods used varying greatly between studies (Chang et al. 2010; Evans, 2011; Villarroya et al. 2009). Moreover, Gilmor and Burns (2001) reported that, while footprint based estimates of arch height were significantly altered in obese children, direct clinical measures of arch height were not. It is also unclear whether static footprint measures can be indicative of dynamic foot function. Mathieson et al. (2004) reported that statically calculated parameters must be viewed with caution as they appear to inconsistently predict the dynamic dimensions of the foot. Furthermore, the authors suggest their relationship to dynamic motion (the variable perceived to be related to the development of foot pathology) remains unclear. This is of particular relevance to obese children where the relationships between static and dynamic measures are likely to be affected and warrants further investigation.

Flippin et al. (2008) aimed to verify whether static footprint measures could predict dynamic plantar pressures in obese and non-obese children, aged 9-to-11 years (N = 20). The authors reported that correlations between static and dynamic measures were observed to be significant ($p<0.05$) for the non-obese children, while no significant correlations were found for the obese children. The authors concluded that static footprint measures should be used with caution when inferring the characteristics of obese children's feet under dynamic conditions and provide little or no information with regards to foot function.

The evaluation of discrete changes in the anthropometric characteristics of the paediatric foot, as a result of childhood obesity, offers understanding of the wider demands placed upon the musculoskeletal system. Mauch et al. (2008) evaluated the static foot morphology of underweight (N = 158), normal weight (N = 2257) and overweight children (N = 456) using a three-dimensional foot scanner. Mauch et al. (2008) reported that increased body mass (as classified by BMI) was associated with larger foot dimensions, indicated by a larger foot volume, length, breadth and circumference. Flat feet, as characterised by a flattened MLA, were also more prevalent in the overweight children however the authors did note that the differences with respect to flat feet were not as obvious as expected based on knowledge from previous studies. Changes in the anthropometric structure of the paediatric foot, associated with obesity, are further echoed in the earlier work of Mickle et al. (2006) and Morrison et al. (2007) where obese children were reported to have longer and wider feet.

The reasons underpinning the structural changes in the feet of obese children are not clear but could be related to a number of factors, including biomechanical deformity, such as pes planus and excess adipose tissue (Morrison et al. 2007). However, there is a growing debate in the literature as to whether the flatter foot structure, evident in obese and overweight children, does actually constitute a lower MLA. One suggestion that has emerged is that the flatter foot characteristics of obese children may be caused merely by the existence of a plantar fat pad underneath the midfoot, giving the appearance of a flatter foot due to a greater ground contact area (Riddiford-Harland et al. 2000).

Early work examining the plantar fat pad of children found no significant difference between normal and overweight pre-school children (Mickle et al. 2006; Wearing et al. 2004). Recently, Riddiford-Harland et al. (2011) compared the midfoot plantar fat pad thickness and MLA height in 75 obese children to 75 age and sex-matched non-obese children. The authors reported that the obese children displayed both a significantly greater midfoot plantar fat pad thickness (4.7mm and 4.3mm respectively, $p<0.001$) and lower MLA (23.5mm and 24.5mm respectively, $p<0.006$) when compared to their leaner counterparts. It therefore appears that obese children have both significantly *"fatter"* and *"flatter"* feet in comparison to normal weight children. However the functional and clinical relevance of the increased fatness and flatness values in the obese child remains unknown. Emerging evidence suggests a causal relationship between arch structure and musculoskeletal pain and injury in obese children and adolescents (Bird and Payne, 1999; Stovitz et al. 2008; Tanamas et al. 2011).

Furthermore, flatfoot involves changes in foot support and can be responsible for clumsiness, tiredness and alterations in gait and a reduction in balance control (MacWilliams et al. 2003; Villarroya et al. 2009).

There is emerging evidence of research that has demonstrated structural changes at the midfoot of obese children, which may affect the functional capacity of the MLA resulting in pes planus (Mauch et al. 2008; Morrison et al. 2007; Riddiford-Harland et al. 2011; Villarroya et al. 2009). However, it is difficult to elucidate the pathways to structural changes of the paediatric foot; an issue which is further complicated by methodological issues and lack of standardisation. To date, the majority of the work has been relatively low powered studies with further work required to address these issues, particularly during dynamic weight-bearing tasks. Furthermore, measures of static footprints offer little information with regards to dynamic foot function and thus links between obesity, foot pathology and foot structure are yet to be elucidated.

2.3.2.5 Foot Loading and Childhood Obesity

The clinical evaluation of the dynamic foot is not without challenges, particularly when attempting to classify foot structure and function and establish relationships to pathology. To characterise and identify alterations in the functionality of the human foot during common activities of daily living, such as walking, plantar pressure measurements generated during such activities are commonly used.

Various authors have suggested that obesity may negatively affect the immature foot structure of children; however, few studies exist that have directly examined the association between plantar foot loading during walking and obesity in children. Early work from Hennig et al. (1994) found significant correlations between body mass and the plantar pressures generated under the feet of 125 children aged between 6-10 years, although the study did not specifically recruit obese participants. Dowling et al.

(2001) investigated the effects of obesity on the plantar pressure patterns generated by 13 obese (8.1 ± 1.2 years) and 13 non-obese (8.4 ± 0.9 years) pre-pubescent children matched by age, gender and height. Dowling et al. (2001) reported that the peak forces generated over the plantar surface of the total foot during walking were significantly greater in the obese children compared to their non-obese counterparts. The authors did note that as this increased force (generated by the obese children) was distributed over a larger total foot area, only negligible differences (43.4 $N.cm^{-2}$ in comparison to 38.8 $N.cm^{-2}$ for the obese and non-obese groups respectively) were found. Nonetheless, when the foot was divided into rearfoot and forefoot sections the obese children experienced significantly greater peak pressures under the forefoot (39.3 $N.cm^{-2}$) compared to the non-obese children (32.3 $N.cm^{-2}$).

These conclusions were confirmed in a later study by Dowling et al. (2004) who reported that obese children (N = 10) generated significantly higher forces over a larger foot area and experienced significantly higher plantar pressures compared to their non-obese counterparts (N = 10) during standing. Whilst walking, the obese children generated significantly greater forces over all areas of their feet, except the toes. Despite distributing these larger forces over a significantly larger foot area, when walking, the obese children experienced significantly higher plantar pressures in the midfoot, heel and 2nd-5th metatarsal heads compared to non-obese children. However, in both cases the authors neglected to present detailed data for specific regions of the foot and failed to conform to the guidelines for the standard units of measurement first proposed by the Foot Pressure Interest Group (Barnett, 1998) and currently recommended by i-FAB in relation to the presentation of foot pressure measurement variables (Giacommozzi, 2011), impacting upon the clinical interpretation and utilisation of these research findings.

Other studies investigating the effects of childhood obesity on plantar pressure distributions during walking in children have also reported significantly higher pressures and forces across different regions of the foot in obese children (Mickle et al. 2006; Yan et al. 2013). Mickle et al. (2006) compared the dynamic plantar pressures generated in 17 overweight/obese children (4.4 ± 0.8 years) and 17 age, gender and height matched non-obese peers (4.4 ± 0.7 years). The authors reported that when walking, the overweight/obese children displayed significantly larger contact areas and generated significantly larger forces on the plantar surface of their total foot, heel, midfoot and forefoot compared to the non-obese children. It was also reported that despite generating these higher forces over larger contact areas, the overweight/obese children displayed significantly higher peak pressures, force-time integrals and pressure-time integrals in the midfoot compared to their leaner counterparts.

More recently, Yan et al. (2013) reported that the peak pressures under the lateral heel, midfoot and 2nd-5th metatarsals were significantly higher ($p<0.05$) in 50 obese children (9.62 ± 1.61 years) when compared to 50 non-obese participants (10.26 ± 0.72 years). The authors reported pressure rate (speed of change in pressure) at the midfoot and heel were significantly higher in the obese group of children. In addition, when plantar pressure distributions were controlled for differences in body weight and foot size (expressed as relative regional impulse), significant group differences were reported at the midfoot (6.20 ± 2.63% and 5.08 ± 1.78% for the obese and non-obese groups respectively) and forefoot (27.23 ± 5.93% and 24.29 ± 9.18% for the obese and non-obese groups respectively) regions. Finally, the authors reported differences in foot pronation (as categorised by increased medial foot loading), where obese children excessively pronated during the stance phase of walking. As a result of these functional differences, Yan et al. (2013) concluded that obese children would be more likely to feel pain and discomfort in the lower extremities including foot, ankle and knee joints resulting in impaired stability during walking.

These studies go some way in presenting baseline data for the foot loading characteristics in obese and non-obese children in order that comparisons can be made whilst also highlighting the increased risk of obese children in developing structural mal-adaptations at the foot. However, comparisons between studies are difficult due to the use of different plantar pressure measurement technology, the adoption of different protocols and the lack of standardisation over the plantar variables reported and the units in which these are expressed in. Additionally, the previous work in this field has limited its analysis to only include obese and normal weight children; to this authors knowledge, no study has yet determined whether children who are overweight display similar changes in foot loading to their obese counterparts.

The increased pressures exerted on the foot of the obese child have the potential to support the clinical analysis of aberrant mechanical function and possibly predict pathology. The findings from the literature are consistent with the view that obese children might be at an increased risk of developing foot discomfort and or pathology (i.e. stress fractures) as a consequence of the increased pressures acting upon the immature musculoskeletal structure of the paediatric foot. A previous study of obese children and adolescents reported foot pain as the second most common musculoskeletal complaint (Stovitz et al. 2008). Similarly in children, a positive association has been reported with regards to foot pain and obesity (Tanamas et al. 2011). Furthermore, foot discomfort and/or pain associated with these increased peak pressures may have additional negative health consequences for the obese child, in-so-much that it may hinder their participation in physical activity. Although speculative, recent research by Mickle et al. (2011) sought to explore the relationship between plantar pressures, physical activity and sedentariness in a sample of 33 children (4.3 ± 0.6 years). The authors reported a significant ($p<0.05$) inverse relationship between peak pressures across the heel and total physical activity ($r^2 = -0.53$) and time spent in moderate-to-vigorous physical activity ($r^2 = -0.47$).

Mickle et al. (2011) suggested that higher plantar pressures in children appear to be a negative correlate of physical activity and exercise behaviour and those children who generated higher peak loading characteristics on the plantar surface of the foot were more likely to suffer pain and discomfort in their feet. Furthermore, foot discomfort and/or pain associated with these increased peak pressures may have additional negative health consequences for the obese child, in-so-much that it may hinder their participation in physical activity as weight bearing activities can become difficult if not appropriately designed to account for these functional changes (Mickle et al. 2011).

Current literature has suggested that obese children are at an increased risk of developing foot discomfort, foot pathologies and/or structural dysfunction, such as a collapse of the MLA, as well as generating increased pressures and forces acting upon the immature musculoskeletal structure of the paediatric foot. However, despite these potentially negative consequences of childhood obesity on foot structure and function; it is currently unknown whether the functional changes to the feet in obese children influence the temporal-spatial, kinematic and kinetic biomechanical function of the entire lower limb and as such affect a child's gait. Consequently, an important contribution to understanding the movement capabilities of obese and overweight children may be provided via gait analysis (Hills et al. 2002) and warrants further analysis.

2.3.3 Paediatric Gait

Obesity has been associated with increased force across weight bearing joints, enhancing the risk of lower limb musculoskeletal disorders. It has been proposed that childhood obesity is associated with gait modifications with several authors identifying differences in the lower limb temporal-spatial, kinematic and kinetic gait parameters of obese children, relative to their normal weight peers, resulting in a slower, safer and more tentative walking pattern (McGraw et al. 2000; Morrison et al. 2008). The following sections will critically review the impact of childhood obesity on the temporal-spatial, kinematic and kinetic biomechanical function of the lower limb during gait. Literature presenting the analysis and reliability of walking and phases of the gait cycle will also be detailed.

2.3.3.1 The Gait Cycle

Gait describes the *"style of walking"* rather that the walking processes itself (Levine et al. 2012). During typical human gait, one limb serves as a mobile source of support, whilst the other limb advances itself, with the limbs then reversing their roles (Perry and Burnfield, 2010). Gait cycle is a repetitive task, where the specific pattern of movement is continually repeated, resulting in motion. A single sequence of one limb supporting the other whilst it advances and the reversal of these roles are defined as a gait cycle (Perry and Burnfield, 2010). The moment at which one foot makes contact with the ground has generally has been selected as the event that defines start of the gait cycle and is referred to as *"initial contact"* (Perry and Burnfield, 2010). Thus more specifically a gait cycle can be defined as the time period from initial contact with the ground of one foot to the subsequent initial contact with the ground of the same foot and the events that occur within that time period (Levine et al. 2012).

Each gait cycle (Figure 2.1, page 39) can be divided into two periods; stance (when the foot is in contact with the ground) and swing (time the foot is in the air). Stance begins with initial contact and swing as the foot is lifted from the floor, commonly referred to as *"toe-off"* (Perry and Burnfield, 2010). The stance and swing phases commonly account for approximately 60% and 40% of the gait cycle respectively (Levine et al. 2012). Stance phase is further sub-divided into three phases, according to periods of single or double leg support (Figure 2.1 below). Both the start and end of stance involve a period of double leg support, whilst the middle period of stance involves a single leg support phase (Perry and Burnfield, 2010). Initial double support begins with contact of both feet on the ground after initial contact and concludes when one foot leaves the floor. Acceptance and absorption of weight whilst preserving forward progression are important tasks during this phase (Levine et al. 2012). A period of single leg support follows, during which the body’s entire weight is supported on one leg. Towards the end of stance phase, the opposite foot returns to the floor and a second period of double leg support commences (terminal double support), continuing until the original stance leg/foot is lifted for swing. Once the foot has left the ground, forward progressions and foot clearance are important tasks during the swing phase (Levine et al. 2012).

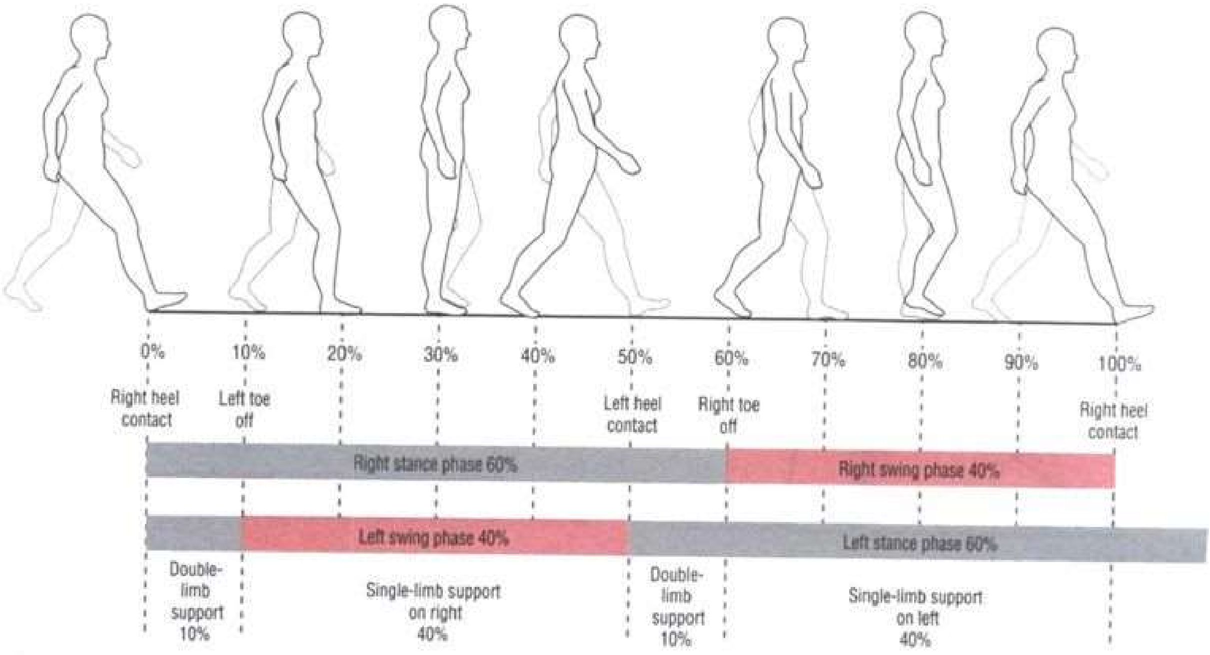


Figure 2.1. Diagram showing the division of the gait cycle, identifying periods of stance and swing. Reprinted from Perry and Burnfield (2010). *Gait Analysis. Normal and Pathological Function* (2nd Ed.), pg. 5, with permission from SLACK Incorporated

2.3.3.2 Analysis of Gait

Clinical gait analysis allows the measurement and assessment of walking biomechanics, which facilitates the identification of abnormal temporal-spatial, kinematic and kinetic movement characteristics (Davies, 1997). Currently the gold standard methodology for gait analysis involves three-dimensional dynamic motion capture systems, where anatomical landmarks are identified by positioning reflective markers on the lateral aspect of the lower limb (Leardini et al. 2007). These systems evaluate movement of the body and its relative segments (hip, knee and ankle) or kinematic variables (joint angles, displacements and velocities) with the kinetics which cause the movement (ground reaction forces and internal or external generated joint moments of force). These together with temporal-spatial parameters (velocity of walking, cadence, step length, width and time and single and double support time) describe the behaviour of the joints and provide an appreciation of the relationship between underlying muscular forces, resultant joint moments and the mechanics of gait and are essential to give a detailed picture of the specific gait characteristics of an individual (Coutts, 1999).

Three-dimensional dynamic motion capture systems are increasingly used to evaluate the patterns of walking in typically developing children (Ganley and Power, 2005; Lythgo et al. 2009; Schwartz et al. 2008; van der Linden et al. 2002) and those with complex gait abnormalities (Gaudreault et al. 2010; McMillan et al. 2010; Shultz et al. 2009; Stephensen et al. 2008). However, as yet, very little is currently known with regards to the temporal-spatial and lower limb kinematic and kinetic gait characteristics of obese and overweight children and how these compare to that of their normal weight peers. Current research has tended to focus on temporal-spatial and kinematic adaptations alone; often at individual weight bearing joints, within a single plane of motion and across the entire gait cycle. To this author’s knowledge, no research to date has examined the temporal-spatial and tri-planar (sagittal, frontal and transverse), lower limb kinematic and kinetic walking parameters of obese and overweight children across multiple phases of the gait cycle, in order to develop a comprehensive three-dimensional approach to the data analysis of the lower limb movement disorders experienced by obese and overweight children.

2.3.3.3 Reliability of Gait Analysis

Young children typically display less consistent gait patterns during repetitive movements and can be distracted more easily during a test situation (Stolze et al. 1998), which could result in a lower reliability of temporal-spatial, kinematic and kinetic gait parameters. A number of other methodological sources have been suggested to contribute towards within- and between-session reliability of three-dimensional gait analysis data, including motion capture system accuracy, marker placement accuracy with respect to anatomical landmarks, soft-tissue artefact (i.e. movement of the skin, muscles and other tissue), thickness of subcutaneous fat, anthropometric measurements, walking speed, data processing techniques as well as subject fatigue, motivation and concentration (Baker, 2006; Della Croce et al. 2005; McGinley et al. 2009; Schwartz et al. 2004).

Evaluating the test re-test reliability of temporal-spatial gait parameters in 12 typically developing children (6.8 ± 0.4 years) using a walkway, Stolze et al. (1998) reported ICCs of 0.35 for gait velocity, 0.74 for stride length, 0.72 for step length, 0.70 for step width, 0.47 for cadence, 0.30 for stance time, 0.69 for swing time and 0.28 for double-support time, which suggests poor-to-moderate re-test reliability of the temporal-spatial parameters. The authors reported greater variability in gait velocity, cadence, stance time and double-support time and suggested the low re-test reliability for the time spent in stance and double-support was due to their very short duration (<0.5 seconds). Similar findings were reported by Thorpe et al. (2005) in 57 typically developing children, aged 1.3-10.9 years, using the GAITRite® electronic walkway. Thorpe et al. (2005) reported ICCs of 0.70-0.75 for gait velocity, 0.62-0.93 for cadence, 0.41-0.88 for stride length, 0.40-0.89 for step length, 0.25-0.60 for single-support duration and 0.57-

0.73 for double-support duration. The authors also reported greater variability in gait velocity, cadence and double-support duration but only in children less than 8-years of age. Children aged 8-11 years demonstrated greater variability in step and stride length.

Steinwender et al. (2000) reported the test re-test reliability of gait data in 20 typically developing children, aged 7-15 years, using a six-camera video based motion capturing system (Motion Analysis Corporation®). The authors reported within- and between-session CoV of 3.4 and 5.7%, 5.2 and 8.8% and 4.0 and 6.2% for cadence, gait velocity and stride length respectively, indicating a greater variability in gait velocity. More recently, Stephensen et al. (2008) reported moderate-to-excellent levels of reliability (ICCs: 0.60-0.97) for the temporal-spatial gait parameters of velocity, cadence, step length, step width, single-support duration and double-support duration using a ten-camera VICON Motion Analysis® system in four normal healthy children (8.05 ± 1.45 years). However, comparison across studies is difficult due to differences in the measurement technologies between motion capture and walkway systems and different statistical methods employed to analyse data.

Stephensen et al. (2008) additionally reported increased re-test reliability in the sagittal plane joint kinematics at the ankle (ICCs: 0.73-0.81) and knee (ICCs: 0.71-0.87) in comparison to the hip (ICCs: 0.61-0.67); the results of which are in contrast to those of Steinwender et al. (2000). Using coefficients of multiple correlation (CMCs), similar within- and between-session reliability were reported in joint kinematics of the hip (CMCs: 0.96-0.98), knee (CMCs: 0.96-0.98) and ankle (CMCs: 0.87-0.93). Furthermore, the authors reported higher reliability in the sagittal plane in comparison to the frontal and transverse planes. Within- and between-session CMCs of 0.90 and 0.85, 0.82 and 0.49 and 0.87 and 0.61 for the hip, knee and ankle in the frontal plane and 0.82 and 0.59, 0.79 and 0.34 and 0.76 and 0.37 for the hip, knee and ankle in the transverse plane were reported. Finally, Steinwender et al. (2000) reported the within-session reliability of joint kinematic parameters was significantly better when compared to that between-sessions (p<0.05).

Comparable findings are described by Mackey et al. (2005) in a group of 10 children (10.5 ± 3.5 years), where within- and between-session CMCs of >0.95 were reported in the joint kinematics at the hip, knee and ankle in the sagittal plane. Reduced within- and between-session reliability was reported in the joint kinematics of the hip, knee and ankle in the frontal (CMCs: 0.70-0.93) and transverse (CMCs: 0.78-0.91) planes. Improved within-session reliability was also reported in comparison to between-session; however the authors did not test for significance. Methodological differences alongside differences in statistical analysis may account for the comparative differences.

Within- and between-session reliability of kinetic parameters is generally higher than those for kinematic parameters (Quigley et al. 1997; Steinwender et al. 2000; Stephensen et al. 2008). Quigley et al. (1997) reported improved re-test reliability in five typically developing children, aged 6-16 years, at the hip (ICCs: 0.67-0.91) followed by the ankle (ICCs: 0.88) and knee (ICCs: 0.71-0.81). The authors also reported improved reliability in the sagittal plane joint kinetics, with the lowest reliability reported in the transverse plane. In the frontal plane, reliability was greatest at the hip joint (ICCs: 0.85) and smallest at the knee joint (ICCs: 0.73), whereas in the transverse plane, reliability was highest at the knee joint (ICCs: 0.71) and weakest at the hip joint (ICCs: 0.67). The authors failed to present frontal and transverse plane data at the ankle. In contrast, Steinwender et al. (2000) reported improved within- and between-session reliability in sagittal plane ankle joint kinetics (CMCs: 0.91-0.94) followed by the hip (CMCs: 0.85-0.96) and knee (CMCs: 0.78-0.93) joints. In both studies reduced reliability in sagittal plane joint kinetics were reported at the knee joint. CMCs of 0.82, 0.78 and 0.91 (Steinwender et al. 2000) and ICCs of 0.91, 0.81 and 0.88 (Quigley et al. 1997) were reported at the hip, knee and ankle joints respectively. Steinwender et al. (2000) also reported the reliability of joint kinetics was significantly higher within-sessions than between-sessions ($p<0.05$). More recently, Stephensen et al. (2008) reported excellent levels of reliability (ICCs: 0.87-1.00) for ground reaction forces and sagittal plane joint kinetic data at the hip, knee and ankle.

A review of the literature has revealed that the collection of reliable temporal-spatial, kinematic and kinetic gait data is possible in typically developing children. However comparisons between studies are limited due to methodological differences including different equipment, marker placement, data processing, filtering procedures and statistical analysis. Furthermore, current research also fails to present within- and between-session kinematic and kinetic data during different phases of the gait cycle and across all three planes of motion at the hip, knee and ankle joints during walking in children.

2.3.3.4 Development of Paediatric Gait

The development and maturation of gait is a complex neurophysiological process (Sutherland, 1988). Independent ambulation is characterised by the ability of an individual to establish a smooth and efficient transfer of the body through space and the integration of multi-sensory inputs such as sight, sound, balance and coordination of the major body segments (Sutherland, 1980).

Dusing and Thorpe (2007) using an electronic pressure sensitive mat to compare the temporal-spatial gait parameters of walking in 438 children, aged 1-10 years, reported normalised walking speed and step length increased until the age of six; however, normalised cadence continued to decrease until 9-years of age. No age related differences were noted in the percentage of time spent in double support. Comparing the temporal-spatial gait parameters of 15 healthy children (7.4 ± 0.4 years) and 15 healthy adults (31.8 ± 6.8 years) using a six-camera VICON motion analysis system, Ganley and Powers (2005) reported that the average walking speeds for both groups were identical, however the children achieved this speed using a significantly greater cadence and significantly shorter step length ($p<0.002$).

In contrast, Lythgo et al. (2009) reported normalised measures of velocity, step length, stride length, base of support, foot angle, step time, stride time, single support duration and double support duration were unaffected by age when comparing 898 children (5-13 years) and 82 young adults (18-27 years). The authors reported that when normalised, gait is relatively stable from the age of 7-years. Similarly, recent work from Bovi et al. (2011) using a nine-camera SMART-E motion capture system reported no significant differences in normalised measures of gait speed, cadence, stride length, step length, stance time and first double support phase when comparing 20 healthy children (10.8 ± 3.2 years) and 20 healthy adults (43.1 ± 15.4 years). However comparisons between studies are difficult due to different approaches adopted for normalisation of data.

With regards to the kinematic patterns of walking in children, Chester et al. (2006) investigated age related differences in sagittal plane gait patterns of 47 typically developing children, aged 3-13 years, using a six-camera, three force plate motion capture system. The timing of the swing phase peak knee flexion, ankle plantar flexion and dorsiflexion angles in children aged 3-4 years were delayed together with greater hip and knee flexion angles compared to the oldest group of walkers (9-13 years), however the differences were not statistically significant. Ganley and Powers (2005) also reported no significant difference in joint kinematics at the hip, knee and ankles were observed between children and adults. These results compare with earlier research (Ounpuu et al. 1991) and suggest no apparent age related differences in kinematic patterns of walking beyond 7-years of age.

In contrast, it has been suggested that kinetic walking patterns may not be established in children until adolescence. Cupp et al. (1999) compared the kinetics of 4-5 (N = 6), 6-7 (N = 7) and 8-10 (N = 10) year old children to a control group of 18-21 year old adults (N = 5) and despite similar walking velocities and normalisation of joint moments to body weight, all groups of children <7-years demonstrated lower hip abduction moments during initial double support, lower knee extension moments during initial double support and single support and lower ankle plantar flexor moments at terminal double support. After 7-years of age, the only differences with adult gait were lower hip abduction moments and knee extension moments; however, by age 10-years, all joint moments resembled adult gait. The previously mentioned work of Ganley and Powers (2005) reported normalised ankle plantar flexor moments of 7-year-old children were significantly lower ($p<0.002$) compared to adults during late stance. No significant group differences were found in the sagittal plane hip and knee moments. The authors suggested that children as young as 7-years lack the neuromuscular maturity at the ankle to produce an adult-like gait pattern.

More recently, Chester and Wrigley (2008) using principle component analysis to explore age related differences in sagittal plane kinetic parameters at the hip, knee and ankle in children aged 3-13 years (N = 47) suggested differences in kinetics persist in children up to 13-years. During late stance, normalised ankle plantar flexion moments increase in magnitude from 3 to 13 years. Knee flexion moments are reduced in young children during early stance and knee extension moments are reduced throughout the stance phase in younger children. Larger hip extension moments in the first third of the gait cycle, smaller hip flexor moments in the middle third of the gait cycle and smaller hip abduction moments during all phases of stance were found in children aged 3-8 years compared to those aged 9-13 years.

This work suggests there are few age related differences in the temporal-spatial and kinematic patterns of walking beyond 7-years of age. However, studies also suggest that kinetic patterns of walking continue to mature until 13-years of age. This may in part be due to inherent variability of growth and development in individual children (Bovi et al. 2011). Due to this, 7-years are most regularly cited regarding the maturation of gait.

2.3.3.5 Temporal-spatial Patterns of Walking and Childhood Obesity

The preliminary work investigating the link between childhood obesity and altered temporal-spatial gait parameters was conducted by Hills and Parker (1991[a,b]). Through this work it was concluded that the obese prepubertal children displayed greater asymmetry in their gait as well as displaying a longer double- and shorter single-limb support period compared with non-obese children. Other temporal differences included a longer cycle duration, lower cadence, lower relative velocity and greater stride width. These results were the first suggestion of a slower, safer and more tentative walking gait in obese children relative to normal weight children.

Further work conducted by McGraw et al. (2000) reported similar findings to the work of Hills and Parker (1991[a,b]), in-so-much that it also reported altered temporal-spatial gait parameters were related to excess body mass in children. The study by McGraw et al. (2000) recruited 20 male subjects (10 obese and 10 non-obese) aged between 8-10 years and evaluated gait using videography. The authors concluded that the obese children spent significantly greater percentage of the gait cycle in double-support and stance ($p<0.02$). Similarly, the swing phase of the obese group contributed significantly less to the gait cycle than was true for the non-obese group ($p<0.02$). The authors also concluded that the mean cadence for the obese boys (65.3 ± 8.1 steps/min) was lower than for the non-obese boys (70.4 ± 6.7 steps/min) although no significant difference was noted ($p=0.14$).

These findings have been echoed in the more recent work of Morrison et al. (2008) investigating the influence of body mass of the temporal-spatial parameters of peripubescent gait in 22 normal weight children and 22 children with excessive body mass, aged 9-11 years. The authors reported temporal-spatial parameters of decreased gait velocity (123.6 ± 10.7 and 129.0 ± 9.9 in children with excessive body mass and normal weight children respectively), in addition to a significantly greater time in double-support ($p<0.05$) and a significantly reduced time in single-support ($p<0.05$) in the children with excessive body mass. In contrast to the work of the previously mentioned authors, Nantel et al. (2006) reported no significant differences for cadence, velocity, stride length and time spent in the double-support phase when comparing the locomotor strategies of 10 obese to 10 non-obese children aged 8-13 years. The authors did note however, that the single support phase duration was statistically shorter ($p<0.05$) in the obese group.

Altered temporal-spatial parameters in obese children may indicate a locomotor strategy that would help maintain medial-lateral stability during gait and suggests that obese children alter their gait pattern to compensate for increased instability. However, the findings reported from the previously mentioned studies must be interpreted with caution due to methodological differences, small sample sizes and methodological inaccuracies with regards to the classification of childhood obesity, all of which would affect the external validity of the work. Further work in this field is required incorporating kinematic and kinetic gait analysis.

2.3.3.6 Kinematic Parameters of Walking and Childhood Obesity

Kinematic joint biomechanics have also shown to be affected by excess mass during normal walking gait in children. Hills and Parker (1991^{c}) reported differences in the sagittal plane joint kinematics of 10 obese children when compared to a group of 10 age-matched normal weight subjects (10.5 ± 2.4 years). A reduction in both hip and knee flexion was reported during both the stance and swing phases in the obese group. It was also reported that knee extension began earlier in the obese children following toe-off; this accompanied with a reduction in ankle dorsiflexion contributed to reduced toe clearance during the swing phase. Hills and Parker (1991^{c}) also reported that the obese children displayed reduced thigh adduction and increased thigh rotation, a more flat-footed weight acceptance pattern in early stance and a greater external rotation of the foot (out-toeing) at all phases of the gait cycle. These results were the first suggestion of a link between movement inefficiency in the gait cycle and decreased stability of obese children.

McGraw et al. (2000) reported similar findings to the work of Hills and Parker (1991^{c}), in-so-much that it was also concluded that instability during gait was related to excess body mass. McGraw et al. (2000) evaluated postural stability via a Kistler force plate during barefoot walking, from the maximum displacement of the centre of pressure in the anterior-posterior and medial-lateral directions. No significant differences were reported in the anterior-posterior direction between groups. In the medial-lateral direction, however, the obese children demonstrated increased instability, as attested by a significantly greater ($p<0.01$) maximum displacement of the centre of pressure. The authors concluded that the obese children displayed significantly greater sway areas in the medial-lateral direction, indicative of decreased medial-lateral stability.

Dynamic and static tests of postural control have also revealed reduced stability in overweight children (Deforche et al. 2009; Goulding et al. 2003). Goulding et al. (2003)

demonstrated that male overweight adolescents (N = 25, 14.8 ± 2.4 years) have poorer balance than those of age and height matched *"healthy weight"* controls (N = 68, 14.9 ± 2.4 years). Using a clinical measure of balance (Bruininks-Oseretsky test) participants were tested during three conditions of static balance (standing on a preferred leg on the floor and standing with a preferred leg on a balance beam – with eyes open and eyes shut) and five conditions of dynamic balance (walking forward on a line, walking forwards on a balance beam, walking forwards heel-to-toe on a line, walking forwards heel-to-toe on a balance beam and stepping over a stick on the balance beam). The authors reported than the overweight adolescents had significantly lower test scores ($p<0.05$) during all conditions of static and dynamic balance. Moderately strong negative correlations were observed between the balance test scores and measures of body mass (r^2 = -0.379, $p<0.01$), percentage body fat (r^2 = -0.319, $p<0.01$) and total fat mass (r^2 = -0.372, $p<0.01$); supporting the view that overweight adolescents have poorer balance than those of healthy weight. The indications from this research were that overweight adolescent males were at an increased risk of falling during normal daily activities.

Similarly, Deforche et al. (2009) evaluated the influence of body mass on balance and postural skills in overweight (N = 25) and normal weight (N = 32) prepubertal boys, aged 8-10 years, concluding that overweight boys displayed lower capacity on several static and dynamic balance and postural skill tests. It has been hypothesised that impaired balance in overweight children is a result of multiple factors including the influence of excess abdominal mass upon centre of mass (Corbeil et al. 2001), and reduced muscular function/strength (Goulding et al. 2003).

The findings of more recent reports on the joint kinematic characteristics of walking in children with excessive body mass are inconsistent. Shultz et al. (2009) reported no significant kinematic differences existed at the hip, knee and ankle joints between a group of overweight (N = 10) and normal weight (N = 10) children (10.4 ± 1.68) in the sagittal, frontal and transverse planes. This is in disagreement with the previous work of Gushue et al. (2005), which reported significantly less ($p<0.05$) knee flexion in 10 overweight children (14.5 ± 5.5^0) compared with 13 normal weight children (21.1 ± 5.0^0). However comparisons between studies are difficult due to differences in the instrumentation used to track joint markers. More recent work from Shultz et al. (2012) investigating the consequences of paediatric obesity on the foot and ankle complex of children (10.4 ± 1.68 years) reported that obese children (N = 10) had significantly less ($p<0.01$) active ankle dorsiflexion that non-obese children (N = 10) during 90^0 of knee flexion (19.57 ± 5.17^0 compared to 29.07 ± 3.06^0). The authors concluded that ankle position is likely impacted during the swing phase of gait in preparation for initial contact. This finding supports the previously mentioned work of Hills and Parker (1991^c) that reported reduced ankle dorsiflexion and a flatter foot at initial contact in the gait of obese children.

McMillan and colleagues (2009, 2010) observed differences in the sagittal and frontal plane lower extremity joint mechanics of overweight and obese children in comparison to healthy weight children. McMillan et al. (2009) reported significant group differences ($p<0.05$) in the frontal plane joint kinematics of seven overweight boys (12.0 ± 0.7 years) when compared to seven boys considered healthy weight (10.8 ± 0.7 years). Boys in the overweight group maintained greater rearfoot inversion (7.03 ± 4.36^0 compared to 5.42 ± 1.20^0), knee abduction (-9.09 ± 5.04^0 compared to -3.50 ± 5.31^0) and hip adduction motion (16.39 ± 11.09 compared to 7.03 ± 1.57^0) throughout stance compared with the boys of healthy weight. It was postulated that hip adduction during stance places the knee in a greater valgus position, thereby increasing the stresses placed upon the joint in the frontal plane and increasing the risk of lower extremity malalignment; however further work to increase our understanding of the mechanics of the lower limb in obese and overweight children is warranted. Additionally, the generalizability of these findings are limited by its small sample size and lack of females recruited within the sample. Further work incorporating a larger cohort of representative children is warranted.

Frontal plane lower extremity joint kinematics demonstrated by McMillan et al. (2009) were re-iterated in a later study investigating the sagittal and frontal plane joint mechanics throughout the stance phase of walking in 18 adolescents who were obese (15.0 ± 1.5 years) and 18 adolescents considered healthy weight (14.6 ± 1.8 years) (McMillan et al. 2010). McMillan et al. (2010) reported altered knee joint kinematics in the frontal plane, as demonstrated by an abducted knee position throughout stance in the obese participants. Peak frontal plane knee angles were significantly different ($p<0.005$) between groups at initial contact (-4.12 ± 4.37^{0} and -0.35 ± 2.46^{0}), during early stance (-0.76 ± 4.32^{0} and 2.99 ± 2.73^{0}) and during late stance (-9.55 ± 7.62^{0} and -0.80 ± 3.94^{0}) for the obese and healthy weight participants respectively. In contrast to those results previously reported, no significant group effects were observed in the frontal plane kinematics at the hip or ankle joints.

McMillan et al. (2010) also reported altered sagittal plane joint kinematics in the obese participants. The obese group demonstrated significantly less ($p<0.005$) knee flexion at initial contact (-1.38 ± 7.35^{0}) in comparison to the healthy weight participants (-7.10 ± 3.41^{0}). It was also observed that the participants who were obese maintained a relatively more extended knee during early stance (-11.26 ± 7.03^{0} compared to -16.09 ± 6.35^{0}) and midstance (-4.17 ± 7.93^{0} compared to -7.22 ± 4.72^{0}). At the hip, participants who were obese remained less flexed/more extended than the healthy weight group throughout stance, however this difference was only significant ($p<0.005$) at initial contact (30.47 ± 9.62^{0} and 18.01 ± 10.50^{0} for the obese and healthy weight adolescents respectively). No significant group differences were reported at the ankle joint complex in the sagittal plane. The authors hypothesised that the extended knee during stance may be a compensation for instability within the knee joint structure and raises concern regarding the structural integrity of the lower extremity joint over time, given the repeated high stresses across the joints likely experienced in children who are obese.

In light of the limitations, these findings indicate greater instability and disequilibrium in obese children during walking. Atypical joint kinematics in the sagittal and frontal plane accompanied with a slower walking speed and longer periods of time spent in double-support are thought to assist with the maintenance of dynamic balance. Such findings are a cause for concern, as obese children are increasingly encouraged to be more active; however it has been suggested that decreased dynamic stability could affect a child's ability to participate in physical activity (McGraw et al. 2000). Further work in this field is warranted incorporating a larger ethnically diverse cohort of male and female participants, examining the tri-planar (sagittal, frontal and transverse) kinematics and kinetics of obese, overweight and normal weight children at the hip, knee and ankle across phases of the gait cycle.

2.3.3.7 Kinetic Parameters of Walking and Childhood Obesity

Current research investigating the link between childhood obesity and altered gait parameters has indicated that obese children experience movement related difficulties. However, gait analysis in children has tended to focus upon spatial-temporal and kinematic adaptations alone. Despite the importance of these parameters, kinetic analysis is imperative to help explain the causes of movement in addition to the mechanics and strategies involved during gait (Nantel et al. 2011).

It would appear reasonable to hypothesise that obese children will experience greater loads on the joints of their lower limbs compared with their normal weight counterparts, in part due to the need to bear excessive mass. Gushue et al. (2005) investigated the effects of childhood obesity on three-dimensional knee joint biomechanics during walking. The authors compared 10 overweight (11.9 ± 1.2 years) to 13 normal weight children (12.2 ± 1.6 years) using an ethnically diverse sample. It was reported that the overweight group demonstrated significantly greater ($p<0.05$) peak internal axial knee force (770.0 ± 241.6N) than the children of normal weight (482.7 ± 98.6N) throughout the stance phase. It was also reported that despite the overweight group walking with a significantly lower peak knee flexion angle during early stance, no significant differences in peak or normalised internal knee extension moments were found between groups (25.8 ± 25.6 Nm and 16.5 ± 8.4 Nm for overweight and normal weight children respectively). However, the overweight children demonstrated significantly greater ($p<0.05$) peak internal knee abduction moments (22.5 ± 10.5 Nm compared to 10.8 ± 5.5 Nm), suggesting they may be unable to compensate for increased force through the knee in the frontal plane. Although not significantly different, normalising the peak internal knee frontal plane moments (body weight multiplied by height), revealed that the overweight group walked with peak normalised knee abduction moments during early stance 40% higher than the normal weight group (2.1 ± 1.3 Nm/kg and 1.5 ± 0.7 Nm/kg respectively). Greater thigh girth caused by increased amounts of adipose tissue was also suggested as a contributing factor to the increased peak internal knee abduction moments. The authors concluded that the overweight children may develop a gait adaptation to maintain a similar knee extension load however they appear unable to compensate for alterations in the frontal plane, which may lead to increased loading at the knee joint complex and a possible precursor to musculoskeletal dysfunction. However these conclusions should be interpreted with caution as Gushue et al. (2005) did not report frontal plane joint kinematics. In addition, the use of adult based cadaver segmental anthropometric parameters in the inverse dynamic calculations of kinetics may affect the external validity of this work.

At present, few studies have investigated the sagittal, frontal and transverse plane lower extremity joint mechanics of obese and overweight children. Shultz et al. (2009) reported significantly greater ($p<0.008$) absolute peak joint moments at the hip (flexor, extensor, abductor and external rotator), knee (flexor, extensor, abductor, internal rotator) and ankle (plantar flexors, invertor, external and internal rotators) when comparing 10 overweight (10.4 ± 1.9 years) and 10 normal weight (10.4 ± 1.6 years) children. When peak internal joint moments were normalised to body weight the aforementioned significant differences between groups were largely eliminated, however significantly greater ($p<0.008$) normalised ankle dorsiflexor moments were still reported in the overweight participants. The authors surmised that because body mass is not proportional to joint articulating surfaces, the absolute peak joint moments indicate a higher level of stress being applied to the weight bearing joints of the lower limb, thereby increasing the risk of skeletal malalignment and the development of varus and valgus angular deformities at the knee joint. This is consistent with previous research reporting increased incidence of Blount’s Disease (Dietz, 1998) and Slipped Capital Epiphysis (Murray and Wilson, 2008) in obese children and adolescents.

Previously mentioned work from McMillan et al. (2010) also reported significant differences ($p<0.007$) in kinetics at all lower extremity joints in both sagittal and frontal planes in adolescents who were obese. Obese participants reported significantly lower normalised plantar flexor moments during late stance (-0.67 ± 0.13) compared to healthy weight participants (-0.88 ± 0.07). Normalised knee flexion moments were significantly lower in the obese group at initial contact (-0.19 ± 0.06 compared to -0.28 ± 0.11) and in late stance (-0.10 ± 0.14 compared to -0.31 ± 0.11). At the hip, obese participants reported significantly lower normalised extension moments at initial contact (-0.43 ± 0.12 compared to -0.72 ± 0.23), significantly higher normalised flexion moments during late stance (0.37 ± 0.16 compared to 0.24 ± 0.08) and exhibited an earlier transition to hip flexion moment compared to the healthy weight group. In the frontal plane, obese participants demonstrated a significantly lower normalised rearfoot inversion moment during late stance (-0.07 ± 0.03) compared to their healthy weight peers (-0.11 ± 0.02). At the knee, obese participants exhibited significantly lower normalised knee abduction moments during early stance (0.03 ± 0.03), midstance (-0.16 ± 0.06) and during late-stance (-0.14 ± 0.06) in comparison to the healthy weight group (0.07 ± 0.06, -0.30 ± 0.09 and -0.27 ± 0.09). Finally, the obese adolescents also exhibited significantly lower normalised hip abduction moments (-0.42 ± 0.12) during early stance compared to the healthy weight participants (-0.55 ± 0.13).

The results in the frontal plane are consistent to those reported in a younger cohort of overweight and healthy weight boys (McMillan et al. 2009), in-so-much that the overweight group demonstrated significantly lower normalised knee abduction moments (-0.04 ± 0.07) versus adduction moments in the healthy weight children (0.13 ± 0.06). Normalised hip abduction moments were also significantly lower in the boys who were overweight at the moment of push-off (-0.27 ± 0.10) compared to the healthy weight boys (-0.55 ± 0.14). Several conclusions were drawn from this body of work. Firstly, it was suggested that the reduced plantar flexor moments in late stance would result in decreased push-off; likely requiring increased contributions at other joints. The increased hip flexor moments reported in late stance in the obese participants was thought to be a compensation to pull the limb into swing rather than push it through the plantar flexors. The earlier transition into hip extension with a concurrent hip flexor moment also reported in the obese group was thought to be a compensation for relatively weak hip extensors. Finally, altered knee abductor moments in the obese participants was postulated to increase the repetitive stresses on the knee joint complex, increasing the potential for pain, damage to knee joint structures and reducing the capacity to participate in regular physical activity.

Nantel et al. (2006) presented kinetic sagittal plane data at the hip, knee and ankle for 10 obese and 10 non-obese children, aged 8-13 years. The obese participants demonstrated significantly decreased ($p<0.05$) energy generation from the hip extensors and increased energy absorption from the hip flexors. The authors concluded that obese children were mechanically less efficient at transferring energy between the eccentric and concentric phases at the hip. Within this study the hip appeared the only joint affected by obesity. The work of the previously mentioned authors suggests that obese children develop a gait adaptation to maintain a similar knee extensor load and take advantage of a passive hip strategy to achieve forward progression during gait. The authors also suggested that a greater muscular force is needed when carrying excessive mass in order to implement a braking mechanism, to remain upright during the stance phase of the gait cycle.

Numerous alterations to the gait pattern of obese children have been observed and these include increased double-stance duration, decreased single-stance duration, increased stride width and differences in joint kinematics. Additionally, it may be that the increased joint moments, particularly at the knee, compromise the structures that control joint stability and could explain the slower more tentative walking pattern displayed in obese children; however the results of which warrant further analysis in order to quantify the effects of overweight and obesity on the joint forces in children and the influence this has on the biomechanics of the lower limb and foot. Further study is also warranted investigating the relationship between dynamic foot function and lower limb joint biomechanics in obese and overweight children.

2.4 Chapter Summary

In summary:

- Childhood obesity is recognised as a major modern health problem in many parts of the world, with the incidence of the condition escalating.

- Debate continues with regards to the optimal method for the assessment of childhood obesity but it is evident that each method of classification warrants its own case.
- The implications of childhood obesity are multiple and can affect different systems of the body. Of particular importance to this research are the implications of childhood obesity upon the musculoskeletal system.
- Current research has identified differences in the plantar foot loading characteristics of obese children during walking, which may cause structural mal-adaptations, compromising foot function. These included:
  - Significantly greater peak pressures and forces generated across the plantar surface of the total foot, heel, midfoot and forefoot, including the 2nd-5th metatarsals.
  - Significantly higher force-time and pressure-time integrals at the heel, midfoot and all metatarsal heads.
- Current research has also demonstrated that obese children displayed altered temporal-spatial characteristics of walking, indicative of decreased medial-lateral stability. Preliminary research regarding the kinematic and kinetic function of the lower limb has suggested that obese children demonstrate differences during gait, which may increase their risk of developing foot and lower limb discomfort or pathologies that may affect their ability to successfully perform activities of daily living. These differences included:
  - Decreased gait velocity and single-support duration alongside increased stride width and time spent in double-support.
  - Altered joint kinematics of reduced hip and knee flexion during stance and swing, reduced ankle dorsiflexion during swing and increased knee abduction and hip adduction motion throughout stance.
  - Altered joint kinetics of significantly greater peak absolute joint moments at the hip (flexor, extensor, abductor and external rotator), knee (flexor,

extensor, abductor, internal rotator) and ankle (plantar flexors, invertor, external and internal rotators) and significantly greater normalised ankle dorsiflexor moments.

Further conclusive understanding can only be presented following plantar pressure, temporal-spatial, kinematic and kinetic analysis during the gait cycle of obese, overweight and normal weight children. In order to assess and report findings related to the influence of childhood obesity upon foot loading and gait it is vital to use equipment that has established levels of validity and reliability. Further information relating to the methods involved in plantar pressure assessment and gait analysis and the reliability of these will be presented in Chapters Three and Four respectively.

CHAPTER THREE: OVERVIEW OF METHODS

3.1 Study Timeline

Figure 3.1 below outlines a timeline for this thesis, providing an overview of the flow through the study and achievement of key study milestones.

Complete Registration
June 2008

School Recruitment
July 2008: Invitation letters sent.
October 2008: Petchy Academy provided permission.
December 2008: Jubilee Primary School provided permission.
January 2009: St Bonadventure's Comprehansive Cahtolic School provided permission.

Subject Recruitment
November 2008: Subject recruitment for Study One completed (N = 57).
May 2009: Subject recruitment for Study Two completed (N = 100).
January 2010: Subject recruitment for Study Three completed (N = 45).

Ethics
November 2008: Initial submission.
February 2009: Response to the ethics comittee and re-submission.
March 2009: Ethical approval granted.

Study One: Establishment of the Measurement Protocols
March-June 2009: Data collection and analysis conducted.
July 2009-February 2012: Chapter write-up.
November 2011-April 2012: Publication in the Journal of Foot and Ankle Research.

Study Two: Assessment of Foot Loading during Level Walking
June-December 2009: Data collection and analysis conducted.
January 2010-May 2013: Chapter write-up.
June-September 2013: Publication in the Journal of Foot and Ankle Research.

Study Three: 3-D Gait Analysis of the Lower Limb during Level Walking
March 2010-March 2012: Data collection and analysis conducted.
April 2011-July 2013: Chapter write-up.

Thesis Write-up & Submission
June 2010-June 2012: Transfer from MPhil to PhD and transfer to write-up status.
June 2011-May 2012: Suspension of studies.
June 2012-February 2014: Review of chapter drafts and development of thesis
March 2014: Thesis submission.

Figure 3.1. Thesis timeline

3.2 Ethical Consideration

This study comparing the foot loading characteristics and lower limb biomechanical walking patterns in obese, overweight and normal weight children, aged 7 to 11 years, during barefoot level walking was approved by the Ethics Committee of the University of East London prior to subject recruitment (**ETH/08/94/0**). A copy of the ethical approval is presented in Appendix 1 (page 199).

3.3 Recruitment and Consent

3.3.1 Schools

Invitation letters and information sheets inviting schools to participate in this research study were sent out to 25 schools in the East London region. Of these 25 schools, the following three agreed to participate:

- The Petchey Academy, Hackney.
- St Bonaventure’s Comprehensive Catholic School, Forest Green.
- Jubilee Primary School, Hackney.

Following this, personal contact was made with the deputy head teachers regarding preliminary consent for the inclusion of the schools in the research. Verbal consent was granted by the deputy head teachers to the researcher (SC) and permission letters were drafted.

3.3.2 Participants

3.3.2.1 Inclusion Criteria

The sampling pool for this research consisted of the three schools previously described, where pupils ranged from 4 to 11 years (Jubilee) and 11 to 16 years (Petchey and St Bonaventure’s) respectively. All male and female children aged 7 to 11 years, within the three schools, were recruited for testing as experimental participants following parental or guardian consent. The recruitment of subjects within study three was limited to the initial sample recruited into study two.

3.3.2.2 Exclusion Criteria

Children were excluded from participation if they disclosed any history of orthopaedic, neurological and/or musculoskeletal problems likely to affect their gait or if they refused to participate. Participants were also excluded if they failed to return both signed parental consent and child assent forms.

3.3.2.3 Study One: Establishment of the Measurement Protocols (Chapter Four)

Following consent from the schools, all were then visited by the researcher where an invitation letter (Appendix 2, page 201), information sheet (Appendix 3, page 203) and consent form (Appendix 4, page 209) were disseminated to all the parents whose children were between the ages of 7 to 11 years. Pupils were advised to return the consent forms within one-week and those who returned a signed form would be included in the research. Child assent (Appendix 5, page 211) was then sought once a signed consent form was returned by the child with a signature from a parent or guardian. Test-retest reliability of the methodological protocols was undertaken in children recruited to studies two (N = 45) and three (N = 12). The participant characteristics are reported in section 4.2.1 (page 88).

3.3.2.4 Study Two: Assessment of Foot Loading during Level Walking (Chapter Five)

Parental consent and child assent was obtained prior to data collection and 100 children within the age range 7 to 11 years were recruited. The participant characteristics are reported in section 5.2.1 (page 101).

3.3.2.5 Study Three: 3-D Gait Analysis of the Lower Limb during Level Walking (Chapter Six)

Subject recruitment was limited to the 100 participants that had been recruited into study two. This was done to enable investigation of the functional relationship between characteristics of foot loading and the three-dimensional biomechanics of the lower limb during walking. Letters of invitation, an information sheet outlining this phase of the study and consent forms were sent to all the parents or guardians of the 100 participants recruited into study two; inviting their children to take part in a testing session at the University of East London that was due to be arranged as part of a school educational visit. Child assent was again obtained in order for the subjects to participate once a signed consent from was returned by the child with a signature from a parent or guardian. In total 45 participants were recruited from the initial sample of 100; the participant characteristics are reported in section 6.2.1 (page 121).

3.4 Data Collection

Test-retest reliability of the methodological protocols was undertaken in a smaller group of children recruited to study two (N = 45) and three (N = 12) and are described in Chapter 4 (page 87).

3.4.1 Anthropometrical Data

The methodologies for anthropometrical data collection adopted in studies two and three are presented below. The measures of height, body mass and skinfolds were performed in both studies. Leg length alongside knee and ankle width measures were only performed in study three.

3.4.1.1 Instrument Calibration

Prior to data collection the measurement equipment was calibrated. A metre ruler and a standard 30 centimetre (cm) Helix ruler were used to test the accuracy of the stadiometer at a number of height ranges, ranging from 30-130cm. There were no inaccuracies between the tools within a range of ±3mm. The accuracy of the scales was assessed with a range of kilogram weights, ranging from 25-75 kilograms (kg). This process indicated the scales were accurate to ±0.5kg over the range. The Harpenden skinfold calliper's were returned to the manufacturer (Baty International, West Sussex, UK) where a service and calibration check was performed. Finally, for study three, bone callipers were tested for accuracy by comparing data using the standard 30cm ruler. This simple process indicated the tools produced similar data across a range of measurements.

3.4.1.2 Materials and Procedure

For study two data collection, the researcher, accompanied by a teaching assistant, set-up the equipment in each school at a location where it was appropriate to do so. Children were then guided from their classroom in pairs, to the research area. During all measurements the teaching assistant remained present in the room. In all cases participants were asked to wear minimal sports clothing (i.e. shorts and a t-shirt) and be barefoot.

For study three data collection, participants were required to visit the University of East London motion analysis lab that was arranged as part of a school educational visit. All equipment was set-up prior to testing by the researcher. Again, children visited the lab in pairs and were accompanied by a teaching assistant, whom remained present throughout. Participants were again asked to wear minimal sports clothing and be barefoot.

3.4.1.3 Height

Height was measured using a portable, calibrated stadiometer in accordance with the protocol described by the Marfell-Jones et al. (2006) in reporting the International

Standards for Anthropometric Assessment. Participants were required to stand with their heels together and the heels, buttocks and upper part of the back touching the spine of the stadiometer during the measurement. It was also ensured that the participants' hair did not interfere with the measurement process. The head was then positioned in the Frankfort Plane by the researcher. The Frankfort plane is achieved when the Orbitale (lower edge of the eye socket) is in the same plane as the Tragion (the notch superior to the tragus of the ear). Positioning the head in the Frankfort plane is achieved by placing the tips of the thumbs on each Orbitale and the index fingers on each Tragion, then horizontally aligning the two. The participants were then asked to take an inspiration (and hold momentarily), during which the sliding bar was then lowered onto the crown of the head and height was recorded to the nearest 0.1cm.

3.4.1.4 Body Mass

Calibrated manual SECA body mass scales were used to measure body weight in kilograms (kg). All participants were weighed whilst barefoot and wearing minimal sports clothing. Results were reported to the nearest 0.5kg.

3.4.1.5 Skinfold Measurements

Harpenden skinfold calliper's (Baty International, West Sussex, UK) were used to measure body fat at the triceps and medial calf. These two-sites were selected as they were the least obtrusive and could be measured whilst the participants wore minimal sports clothing. To standardise skinfold measurements, guidelines for the anatomical location of the skinfold sites and measurement technique were used (Marfell-Jones et al. 2006). The triceps and medial calf measurements were taken via a vertical fold on the posterior midline of the upper arm, halfway between the Acromion and Olecranon processes, with the arm held freely to the side of the body and via a vertical fold at the maximum circumference of the calf on the midline of its medial border respectively. Each skinfold site was marked with a fine-tipped felt pen to minimise location errors for repeat measurements. This technique also involves gently pinching the skin with the thumb and forefinger, so that a double fold of skin plus the underlying subcutaneous adipose tissue is held between the thumb and index finger, pulling it away from the body and placing the callipers on the fold. Care was taken not to incorporate underlying muscle tissue in the grasp or pinch. The skinfold calliper's were placed 1cm away from the pinching fingers and held at 90^0 to the surface of the skinfold site at all times, ensuring that the hand grasping the skinfold remained holding the fold the entire time the calliper was in contact with the skin. The measurement was then recorded two seconds after the full pressure of the calliper was applied. The callipers measure the thickness of the two layers of the skin and underlying subcutaneous fat to the nearest 0.1mm. In all cases the right side of the body was used for measurements, with two measurements taken at each site. A third measurement was taken where the second measurement was not within 5% of the first (Marfell-Jones et al. 2006).

3.4.1.6 Weight Classification

Participants were classified in accordance with their Body Mass Index Standard Deviation Score (BMI-SDS). A standard deviation or z-score represents the number of standard deviations that a child is from the expected BMI for age from the 1990 British Growth Reference data (Freedman et al. 1995) and enables standardisation of data for age and gender (Dinsdale et al. 2011). For example, a boy aged 10-years, with a BMI of 21.7kg/m^2, would be assigned a BMI SDS score of +2.0, indicating that his BMI is two standard deviations above the expected BMI for a boy of that age (Dinsdale et al. 2011). This method has also been shown to be the optimal BMI measure for assessing adiposity on a single occasion in children (Cole et al. 2005).

Firstly, BMI was calculated as weight in kilograms divided by the square of the height in metres (Reilly et al. 2010); BMI-SDS values were then derived using a LMS Transformation Programme Software (http://www.phsim.man.ac.uk/ChildObesity/, accessed October 2008). This method summarises the distribution of a measurement as it changes according to age and is represented by three age specific reference centile curves: L (lambda), M (mu) and S (sigma) (Cole and Green, 1992). Barlow and Dietz (1998) proposed a BMI-SDS score of greater than the 85th percentile as being overweight and greater than the 95th percentile as being obese; consequently values of -1.64-1.03. 1.04-1.64 and >1.64 were used to classify normal weight, overweight and obese children respectively.

To support the BMI-SDS classification of weight status; protocols to measure Body Fat % (BF %) were developed using skinfold calliper's to measure body fat at the triceps and medial calf. The skinfold measurement were then converted into a BF% score using the equations (below) developed by Slaughter et al. (1988):

- Males: BF% = 0.735 (sum of skinfolds) + 1
- Females: BF% = 0.610 (sum of skinfolds) + 5

3.4.1.7 Leg Length

Leg length was measured, using a measurement tape, between the anterior superior iliac spine and the medial malleolus of the ankle.

3.4.1.8 Knee and Ankle Width

Bone Callipers were used to measure knee width between the lateral and medial epicondyles and ankle width between the lateral and medial malleoli.

3.4.2 Plantar Pressure Assessment

3.4.2.1 Measurement Apparatus

In order to differentiate the pattern and characteristics of foot loading relative to body mass in prepubescent children, the MatScan® 3150 pressure distribution platform (TekScan, USA) was used to measure the foot loading characteristics of obese, overweight and normal weight children, aged 7-11 years. This system consists of a 5mm thick floor mat (435 x 368mm), comprising of 2288 resistive sensors (1.4 sensors/cm^2), with a pressure range of 10-1800kPa and a sampling frequency of 40 Hertz (Hz). The validity of this system has been established in an independent study which compared several commonly used plantar pressure measurement systems (Giacommozzi, 2010). The reliability of this system has also been established in adult (Zammit et al. 2010) and child (Cousins et al. 2012) populations.

3.4.2.2 Instrument Calibration for Plantar Pressure Assessment

Prior to data collection a new calibration was performed for each new participant's session. The calibration was performed according to the method recommended by the MatScan® (TekScan, USA) manufacturer. The weight of the participant was recorded and entered into the research software. The participant was then required to stand on the pressure platform barefoot and relaxed, adopting a unilateral stance whilst the software applies the appropriate scaling to the raw outputs of the sensing elements such that the total force applied to the MatScan is consistent with the weight of the subject. The raw digital output of the sensor was then converted to actual units of pressure (kPa) and force (N).

3.4.2.3 Experimental Procedures for Plantar Pressure Assessment

Protocols for the assessment of plantar pressures in children were adhered to in this study (Cousins et al. 2012). All children were asked to walk barefoot along a 5-metre walkway with the MatScan® 3150 pressure distribution platform placed on a firm, level surface, in the centre of the walkway. Participants were asked to strike the platform with their fourth step to ensure a constant velocity had been reached prior to contact with the platform (Bryant et al. 1999). This protocol allows a more accurate reflection of a subjects' gait in comparison to abbreviated gait protocols, such as the first-step and two-step methods (Wearing et al. 1999). Abbreviated gait protocols have also been shown to significantly reduce peak pressures and forces beneath the feet during walking (Martin and Marsh, 1992); subsequently the data obtained during these methods may not be generalizable to normal walking conditions (Morlock and Mittlemeiser, 1992; Rodgers, 1985 as cited by Wearing et al. 1999). Given the suggestion that steady state gait is not achieved until the end of the second or third step (Wearing et al. 1999), gait protocols should ideally involve a minimum preamble of at least three steps if representative gait patterns are to be obtained.

All participants were given time to familiarise themselves with the process of walking over the platform to ensure they were comfortable with the experimental procedure. During data collection the participants were encouraged to adopt a natural gait pattern and to walk at a self-selected speed. No attempt was made to control the speed of the participants as previous work with children (1-10 years) demonstrated increased gait asymmetry when precise gait instructions were given (Bosch et al. 2010; Goble et al. 2003). Each participant walked barefoot over the platform, with the position of the platform adjusted to allow participants to strike the platform with their fourth step, with five steps also being taken following platform contact. Trials were excluded and repeated if a participant appeared to target the platform and alter their gait pattern to ensure full contact with the mat, if the participant paused on the mat whilst walking, or if the participant did not continue to walk past the mat with at least five steps. Three complete trials of the right foot were recorded for each participant, as this number of trials has previously been found to be sufficient in ensuring adequate reliability of force and pressure data in children (Cousins et al. 2012). To satisfy assumptions of data independence (Menz, 2004), data from the dominant foot was collected; this was the right foot for all participants. All data was transferred directly to a laptop computer where it was saved for analysis.

3.4.2.4 Data Management for Plantar Pressure Assessment

Due to the absence of a common consensus for the selection of plantar pressure variables, the spatial measures of peak pressure (kPa) and peak force normalised for body mass (N/kg) alongside the temporal measures of pressure-time integrals (kPa/s) and force-time integrals (N/s) were selected for this research. The measure of peak force determines location/s on the plantar surface of the foot that are exposed to high loading and also describes the overall loading effect on structures of the foot. Peak pressure will determine the effect that force has over a specific anatomical area, such as the midfoot, describing the potential damaging effect to the soft-tissue. The temporal measures of pressure-time and force-time integrals will give an indication as to the effects of the peak loading values and provides insight pertaining to the integrity of the soft-tissue and joint structures of the foot. These variables have been recommended in the adoption of “best practice” within the i-FAB community (Giacomozzi, 2011), have previously been used within investigations studying the effects of childhood obesity (Dowling et al. 2001, 2004; Mickle et al. 2006) on plantar pressure distributions and have been found to be of importance in the development of pathological foot problems (Turner et al. 2003; Zammit et al. 2010).

Following data collection, MatScan® Research Software version 6.4 was used to construct individual foot masks to determine plantar loading characteristics under seven discrete regions of the foot: lateral heel (LH), medial heel (MH), midfoot (MID), 1st metatarsophalangeal joint (1MTPJ), 2nd-5th metatarsophalangeal joint (2-5MTPJ), hallux (HAL) and the 2nd-5th toes (TOES) (Figure 3.2, page 71) to provide detailed information regarding the plantar loading of different segments of the foot. Once this template had been performed on an individual footprint, for each participant, it was then saved and used repeatedly for analysis on further trials. It should be noted that for each participant an individual foot mask was constructed; this was then saved and used across repeated trials. Saved foot masks were not used interchangeably between participants. All footprints were masked by the lead author who applied the same foot mask across all trials for each participant. A single rater was chosen to perform all the manual masking so as to reduce the potential for introducing variability into the data, with previous research showing good reliability of a manual mask application being possible when performed by a single rater (Deschamps et al. 2009; Zammit et al. 2010).

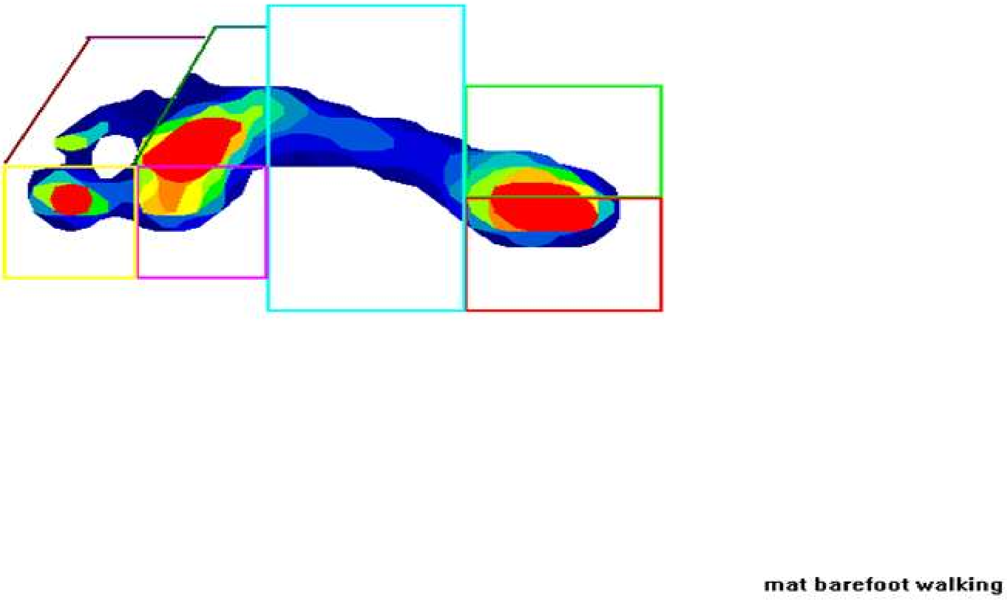


Figure 3.2. An example of a typical walking trial produced by the TekScan MatScan® system, displaying the seven masked regions used during analysis

3.4.3 Temporal-spatial, Kinematic and Kinetic Gait Analysis

3.4.3.1 Measurement Apparatus

Gait analysis was performed using a 10-camera VICON 612 Motion Analysis System (Oxford Metrics Ltd, Oxford, UK). As participants walked along a designated eight metre walkway, the three-dimensional path of 16 reflective joint markers placed on the participants skin were recorded by the cameras at a frequency of 100Hz. Each camera lens contains a circular set of diodes which emit a light that is reflected back from the markers to the camera. The reflected light, converted into video signal and processed in the VICON data station, is transferred to VICON workstation for visual reconstruction. Two Bertec Force Platforms (Model 420 H; MIE Ltd, Leeds, UK) were embedded into the middle of the walkway. Ground reaction forces (i.e. the external forces opposing the forces experienced by the weight-bearing limb) were collected from the force platforms at 1500Hz. The reliability of these laboratory protocols has been previously established in a group of normal healthy children (Stephensen et al. 2008).

3.4.3.2 Instrument Calibration for Gait Analysis

At the start of each test session the motion camera's and force platforms were calibrated and the global fixed co-ordinate system defined. An L-shaped static calibration frame, consisting of four reflective markers, placed at present locations on the frame and embedded spirit levels, was positioned at the corner of one of the force platforms in the centre of the camera capture volume. Marker visibility and static camera calibration were checked and the global co-ordinate system for the laboratory was. A dynamic calibration was then performed with a T-shaped calibration wand consisting of a marker on each end of the wand which was moved continuously through the camera capture volume until 10,000 frames of data were recorded. Testing proceeded if wand visibility exceeded 65%, mean residual exceeded 1.5% and static marker reproducibility was less than 1%. Analogue force platform signals were calibrated and offset loads zeroed using the auto-zero function on the force platform amplifier.

3.4.3.3 Experimental Procedure for Gait Analysis

In order to compare temporal-spatial and lower limb kinematic and kinetic walking patterns in obese, overweight and normal weight children, this research project built upon the robust protocols described by Stephensen et al. (2008) within their analysis of the biomechanical gait parameters of haemophiliac children and healthy age matched controls.

During all data collection trials, participants were barefoot and wore shorts to facilitate the visibility of the reflective joint markers. As previously described (Section 3.3.1, page 62) anthropometric measures of height, body mass, leg length and knee and ankle width were recorded. The participants donned a standard clinical marker set (Plug-in Gait model, VICON Motion Systems, Oxford, UK). The Plug-in Gait (PiG) model is a modified version of the Newington-Helen Hayes gait model and was first described as a protocol for assessment of lower limb kinematics by Davis et al. (1991). The conventional lower limb model (PiG) involved anthropometric measures of knee and ankle width, between-ASIS distance and the vertical distance in the sagittal plane between the ASIS and greater trochanter. Markers were placed on specific bony landmarks defining the frontal plane of the lower limb. The hip joint centre calculation was based on an algorithm from radiographic examination of 25 hips and was a function of leg length. The knee and ankle joint centres were calculated based on the frontal plane joint width measurements. The limb rotation algorithm was based on the determination of Euler (Cardan) angles with a Y-X-Z axis. The transformation matrix which defined the orientation of a particular set of coordinate axis was developed and employed to yield the joint angles corresponding to flexion/extension, adduction/abduction and internal/external rotation respectively. Trunk and pelvis angles are absolute angles referenced to the fixed laboratory coordinate system. The hip, knee and ankle angles were all relative angles. The PiG model was developed using the minimum number of markers possible to determine 3D kinematics and kinetics of the lower limb, because at the time the camera systems were only capable of detecting a small number of markers (Baker, 2006). This model is still widely used for gait data acquisition (Ferrari et al. 2008) and has been validated in numerous scientific reports (Collins et al. 2009; Davis III et al. 1991; Kadaba et al. 1990; Schwartz et al. 2004).

Sixteen reflective infrared markers, 14mm in diameter, were attached directly to the skin using double-sided tape to each participant bilaterally on the anterior superior iliac spine, posterior superior iliac spine, lateral condyle of the knee, lateral malleolus of the ankle, dorsum of the head of the second metatarsal, posterior surface of the calcaneus, midline of the lateral thigh and lateral distal third of the tibia (Figure 3.3 below). The same marker set has been previously used in a number of studies investigating the biomechanical gait kinematics and kinetics in children (Ganley and Powers, 2005; Stephensen et al. 2008). These markers provide an axis system defined by a local coordinate system (LCS) for each segment. The origin and orientation of the LCS was specified in the global coordinate system (GCS). Knee flexion axis was determined from thigh markers and ankle flexion axis from those on the lower leg. In all cases, participant preparation was performed by the researcher (SC) in order to account for differences in marker placement between different investigators and to minimise measurement variability and error (Baker, 2006; Della Croce et al. 2005; McGinley et al. 2009).

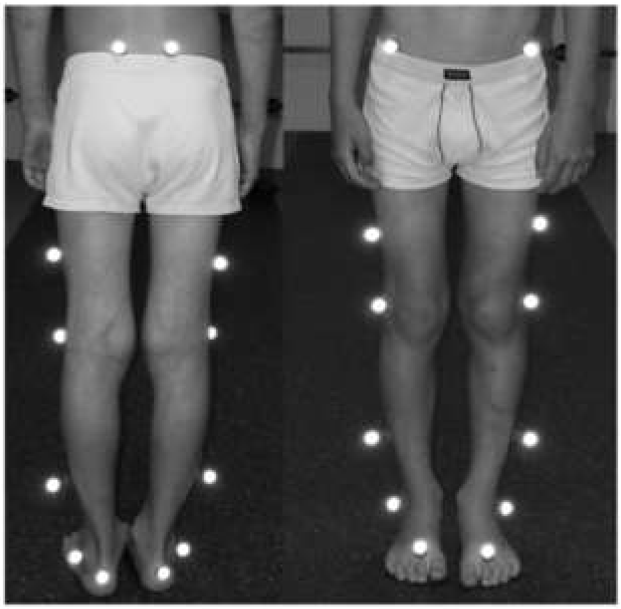


Figure 3.3. Model demonstrating the position of reflective markers for recording of gait analysis

Each participant was instructed to walk at a self-selected comfortable walking speed along the walkway. No attempt was made to control the walking speed of participants, as this has been found to alter normal biomechanical gait parameters in children (van der Linden et al. 2002). Subjects were permitted practice trials to familiarise themselves with the experimental procedures, prior to walking trials being recorded. A single trial was considered successful if two sequential full steps were simultaneously captured by the cameras and force plates. The stride cycle was defined from foot contact of one foot to subsequent foot contact of the same foot and all events were expressed as a percentage of the stride cycle (Shultz et al. 2011). Data from three good trials were saved in VICON Workstation for subsequent analysis, as this number of trials has previously been found to be sufficient in ensuring adequate reliability of temporal-spatial, kinematic and kinetic data in normal healthy adults (Kadaba et al. 1989) and children (Stephensen et al. 2008). Reflective markers were manually labelled and trajectories filtered using a Woltring filtering process (Woltring, 1986). All recordings, instructions and data processing were performed by the researcher (SC).

3.4.3.4 Data Management for Gait Analysis

The anthropometric measures and the reflective marker set attached to the anatomical landmarks described earlier, were used to define the local embedded orthogonal coordinate system for the pelvis, thigh, lower leg and foot segments such that the y-axis represented the flexion-extension axis, the x-axis the abduction-adduction axis and the z-axis the internal-external rotation axis in line with the International Society of Biomechanics (ISB) recommendations for the description of lower limb kinematics (Wu et al. 2002). The three-dimensional global coordinate system (GCS) was defined in the gait laboratory such that the y-axis was along the walkway and positive for the direction of anterior-posterior (AP) progression, the z-axis vertical (V) and x-axis (ML) perpendicular to these axes and positive in the medial direction during contact of the right foot with the walkway (Figure 3.4, page 76).

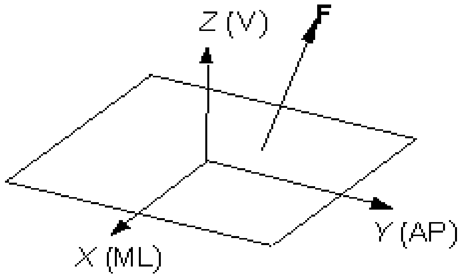


Figure 3.4. The three-dimensional global fixed coordinate system defined in the gait laboratory

Data from one leg was selected for data analysis; this corresponded to the subsequent foot that was selected during the assessment of plantar pressures; in all cases this was the right leg for each participant. Temporal-spatial parameters were determined from motion capture data. Kinematic data was calculated using a seven link rigid segment method. The position of each rigid segment was defined on a frame-by-frame basis from an origin in the GCS and the three orthogonal axis directions. The three axes directions are defined using two directions derived from the marker data. One of these directions is taken as a dominant or primal direction and used to define one of the axes in the segment. The second direction is subordinate to the first and is used with the first direction to define a plane. The third axis of the segment is taken perpendicular to this plane. Then the second axis can be found perpendicular to the first and third axes.

Relative joint angles for the hip, knee and ankle were determined using the Y-X-Z Euler (Cardan) angles derived by comparing the relative displacement (rotations) of adjacent segments about a defined joint axis. The angles can be described as one rotation fixed in either segment, and one *"floating"* rotation. The proximal segment axes are fixed and distal segment moves for relative rotations. A joint angle is then determined using the following ordered rotations: 1) The first rotation (flexion) is made about the common flexion axis; 2) The second rotation (abduction) is made about the abduction axis of the moving segment and 3) The third rotation (rotation) is made about the rotation axis of the moving segment. All axes and segments involved in the calculation of hip, knee and ankle angles adopted in this research project are described in Table 3.1 (page 79). Kinematic variable definitions adopted by the PiG model are also visually represented in Figure 3.5 (page 78).

External joint moments for the hip, knee and ankle were calculated using the principles of inverse dynamics from values of external force applied to the limb (ground reaction force data obtained directly from the two force plates), kinematics of limb segments and distribution of mass within the limb segment (estimated segmental inertial properties). Segmental inertial properties were estimated from anthropometric data where the kinetic modelling of PiG assigns masses and radii of gyration to the segments defined in the kinematic model. The masses of each segment are calculated as a proportion of the total body mass, with estimates made for the radii of gyration due to the lack of experimental data.

Results were displayed as graphs and numerical data using VICON Polygon Plug-in-Gait software, saved in ASCII format and transferred to Microsoft Office Excel (2010) and SPSS Version 15.0 for analysis. The temporal-spatial variables of velocity (metres per second, m/sec), cadence (steps per minute, steps/min), step length (m), step width (m) and time spent in single and double support (sec) were selected for statistical analysis. The influence of body size on spatial-temporal parameters were normalised to dimensionless values, as described by Hof (1996). Length parameters were normalised to leg length, time parameters to leg length multiplied by acceleration due to gravity $(9.81\text{m.s}^{-1})^{½}$ and velocity and cadence to acceleration due to gravity divided by leg length^{½}. The kinematic data of maximum and minimum joint angles and the kinetic data of maximum and minimum external joint moments at the hip, knee and ankle respectively were analysed during initial double-support (IDS), single-support (SS), terminal double-support (TDS) and swing (SW) phases of the gait cycle in the sagittal, frontal and transverse planes. Joint moments were normalised to subjects' body mass and expressed as external moments. Peak vertical ground reaction forces were analysed during IDS, SS and TDS. IDS was defined at the initial contact (heel strike) of one foot, with the contact of both feet on the floor and conclude when the opposite foot leaves the floor (Perry and Burnfield, 2010). A period of one leg support follows (SS), during which the entire body weight is supported on one leg. TDS then begins when the opposite foot returns to the floor (heel strike) and a second period of two leg support commences; continuing until the original leg/foot is pushed off the floor (toe-off) (Perry and Burnfield, 2010). The SW phase applies to the time the foot is in the air for limb advancement and was defined from the toe-off of one foot to the subsequent heel strike (initial contact) of the same foot (Levine et al. 2012).

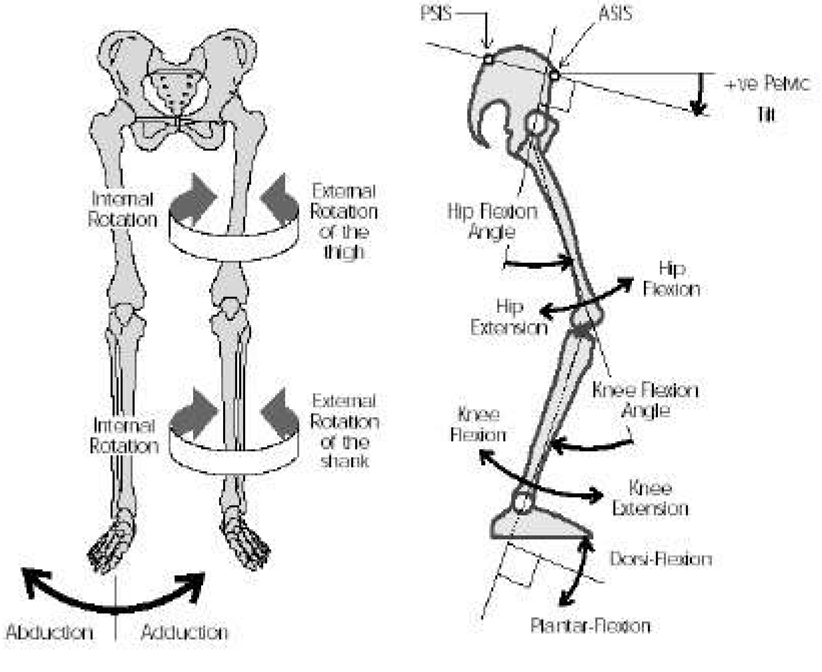


Figure 3.5. PiG kinematic variable definitions. Reprinted from Plug-In Gait Manual, with permission from VICON Incorporated

Table 3.1. Kinematic variables calculated by PiG including information describing axes and segments involved in joint angle calculations

Angle Rotation	Angle Definition
Hip Flexion/Extension	Hip flexion is calculated about an axis parallel to the pelvic transverse axis which passes through the hip joint centre. The sagittal thigh axis is projected onto the plane perpendicular to the hip flexion axis. Hip flexion is then the angle between the projected sagittal thigh axis and the sagittal pelvic axis.
Hip Adduction/Abduction	Hip adduction is measured in the plane of the hip flexion axis and the knee joint centre. The angle is calculated between the long axis of the thigh and the frontal axis of the pelvis projected into this plane.
Hip Rotation	Hip rotation is measured about the long axis of the thigh segment and is calculated between the sagittal axis of the thigh and the sagittal axis of the pelvis projected into the plane perpendicular to the long axis of the thigh.
Knee Flexion/Extension	The sagittal shank axis is projected into the plane perpendicular to the knee flexion axis. Knee Flexion is the angle in that plane between this projection and the sagittal thigh axis.
Knee Adduction/Abduction	This is measured in the plane of the knee flexion axis and the ankle centre, and is the angle between the long axis of the shank and the long axis of the thigh projected into this plane.
Knee Rotation	Knee Rotation is measured about the long axis of the shank. It is measured as the angle between the sagittal axis of the shank and the sagittal axis of the thigh, projected into a plane perpendicular to the long axis of the shank.
Ankle Flexion/Extension	The foot vector is projected into the foot sagittal plane. The angle between the foot vector and the sagittal axis of the shank is the Foot Dorsi/Plantar Flexion.
Ankle Adduction/Abduction	This is the angle between the foot vector (projected into the laboratory's transverse plane) and the sagittal laboratory axis.
Ankle Rotation	This is measured about an axis perpendicular to the foot vector and the ankle flexion axis. It is the angle between the foot vector and the sagittal axis of the shank, projected into the foot transverse plane.

3.5 Data Analysis

Statistical analysis was conducted using SPSS version 15.0 for Windows (SPSS Inc., Chicago, USA). Prior to inferential analysis all data was assessed for normality of distribution using the Kolmogoroff-Smirnoff one-sample test. Variables for analysis were height, weight, BMI-SDS values, peak pressure, normalised peak force, pressure-time integrals and force-time integrals and the selected temporal-spatial, kinematic and kinetic characteristics of the lower limb in obese, overweight and normal weight children. In all cases all variables demonstrated normal distribution.

3.5.1 Evaluating Within- and Between-session Reliability of the Protocols

Within- and between-session reliability of the protocols outlined in sections 3.4.1 (page 63), 3.4.2 (page 67) and 3.4.3 (page 71) was undertaken in a smaller group of children recruited to study two (N = 45) and three (N = 12) and are reported in Chapter 4 (page 87). Within-session reliability was determined from the original testing session using repeated measure ANOVA's to calculate Intraclass Correlation Coefficients (ICC model 3,1). For all the measured variables ICC model 3,1 was selected for analysis, since there was only one rater of interest and analysis was conducted across single ratings (Portney and Watkins, 2000). Variability in the data was assessed via the calculation of Coefficients of Variation (CoV); this analysis of absolute reliability provides information regarding within-trial variability expressed as a percentage.

To assess systematic differences between sessions, individual t-tests were used to compare the mean values of all the measured variables, with statistical significance being defined as $p<0.05$. Between-session reliability was evaluated using both relative reliability statistics (ICC model 3,3) derived from repeated measure ANOVA's and absolute reliability statistics (mean difference and CoV) using the mean of three trials derived from each testing session. All of these techniques have previously been shown to be accepted methods for determining reliability between testing sessions (Benedetti et al. 1998; Portney and Watkins, 2000). Interpretation of the within- and between-session ICCs (3,1 and 3,3) was conducted in accordance with Portney and Watkins (2000), whereby values of >0.75 indicate good reliability, values ranging from 0.5 to 0.75 imply moderate reliability and values <0.5 suggest poor reliability. CoV provide information regarding between-trial variability expressed as a percentage thus enabling direct comparisons between variables measured in different units. The mean difference was also calculated to provide an indication of the overall change in the scores that occurred between each testing session.

3.5.2 Comparative Analysis of Plantar Foot Loading Characteristics and Temporal-spatial, Kinematic and Kinetic Walking Patterns in Obese, Overweight and Normal Weight Children

Means ± standard deviations (SD) were calculated for each measured variable from three repeated trials across a single testing session. A one-way Analysis of Variance Test (ANOVA) was used to test for significant differences in the selected variables between obese, overweight and normal weight children. This test is commonly applied when three or more independent group means are compared (Portney and Watkins, 2000). Height, body mass and BMI-SDS values were compared in studies two and three of the research. In study two the measures of peak pressure, peak force, normalised peak force, pressure-time integrals and force-time integrals were selected for analysis in comparison to temporal-spatial variables of velocity, cadence, step length, step width and time spent in single- and double-support, kinematic data of maximum and minimum joint angles and the kinetic data of maximum and minimum external joint moments at the hip, knee and ankle in study three. If such differences existed, Tukey post-hoc tests were used to ascertain the location of the difference between the three groups. This test offers generous protection against Type I errors (Portney and Watkins, 2000). In all cases, the accepted level of significance was set at $p<0.05$.

3.5.3 Cluster Analysis of Plantar Foot Loading Data

To help characterise differences in the plantar foot loading characteristics in obese, overweight and normal weight children cluster analysis was performed on the data. Cluster analysis is a multivariate statistical method that provides an objective, quantitative classification system by separating individuals into homogenous groups or *"clusters"* based on selected input parameters (Mulroy et al. 2003). The use of cluster analysis to characterise paediatric foot loading has received relatively little attention within the literature. There are many approaches to using cluster analysis; with hierarchical and non-hierarchical methods frequently used on selected specific kinematic and kinetic gait parameters. More recently, Mauch et al. (2008) and Toro et al. (2007) suggested a combination of hierarchical and non-hierarchical techniques as the preferred methods for categorising kinematic and kinetic gait data, including foot loading.

Hierarchical cluster analysis (Ward's linkage method and the Squared Euclidean distance measures) was performed on the foot loading characteristics of the subjects recruited into Phase Two of the research. Hierarchical clustering established the number of clusters and profiles of the cluster centres (Ferrarin et al 2012; Kinsella and Moran, 2008). Ward's linkage method is a minimum difference hierarchical method which calculates the sum of squared Euclidean distances from each case in a cluster to the mean of all the variables (Garson, 2012). The cluster to be merged is the one which will increase the sum the least (Garson, 2012). As such, it adopts an ANOVA-type approach which maximises between-group differences and minimises within-group differences (McLachlan, 1992). This method is also the most suitable to create clusters from smaller samples (McLachlan, 1992). This choice was then confirmed by visually inspecting a dendrogram.

Dendrograms, also referred to as hierarchical tree diagrams, are frequently used to visually illustrate the arrangement of clusters produced by hierarchical clustering and depict the process of going from individual cases to larger clusters across multiple levels (McLachlan, 1992). With a dendrogram, a relationship between individual cases is usually represented by a branching diagram, with each branch containing one or more case that are similar to each other. Further branches can be added to connect original clusters with the height or length of the branch indicating how similar each case is from one another (Garson, 2012). Therefore, every case within an original cluster is more similar to other cases that join at later levels. Dendrograms are usually depicted horizontally, with each row on the Y-axis (vertical) representing a data case or participant, with the X-axis (horizontal) representing the relative size of the coefficient at which individual cases are clustered. The greater the distance coefficient (along the X-axis) the more clustering involved combing unlike entities which is undesirable (Garson, 2012). Consequently, variables or participants with low distances along the X-axis of the dendrogram, indicate they are agglomerated into a cluster at a low distance coefficient indicating a likeness. Conversely, when the branch or linking line is further along the X-axis, the clustering occurs at a higher distance coefficient, indicating clusters are agglomerated even though they are much less alike.

The variables selected for analysis were peak pressure, normalised peak force, pressure-time and force-time integrals across six regions of the foot (LH, MH, MID, 1MTPJ, 2-5MTPJ and HAL). Non-hierarchical (K-means) cluster analysis was then performed to identify which of the subjects belonged to which cluster, as advocated by Mauch et al. (2008). K-means cluster analysis is a type of *“relocation clustering method”* and determines the placement of participants in a pre-specified number of clusters using squared Euclidean distances to the mean of the cluster (Garson, 2012). This process continues until cluster means do not shift more than a given cut-off value (<2%) (Garson, 2012). This method also minimises within cluster variance and maximises variability between clusters in an ANOVA-like fashion (McLachlan, 1992). ANOVA's were then performed on the cluster centres, in order to highlight any significant differences between any cluster groups ($p<0.05$). Cluster centres are the average value of each variable for each cluster's member (Garston, 2012).

3.5.4 Establish Functional Relationships between the Characteristics of Foot Loading and the Biomechanics of the Lower Limb during Walking

As yet it is unknown whether changes to plantar loading in the feet of overweight and obese children can predict lower limb kinematic and kinetic walking patterns. To further understanding on the use of plantar pressure assessment in predicting biomechanical differences in the walking patterns of overweight and obese children, significant relationships between foot loading and the lower limb kinematic and kinetic gait characteristics were evaluated in the overweight and obese participants recruited into study three of the research project. These results could be used as a foundation to inform clinical practice, as plantar pressure assessment offers a cheaper alternative to three-dimensional gait analysis, in the first line of clinical assessment when assessing lower limb function in children; thereby potentially increasing the access to clinical services for these children.

First, significant relationships between normalised peak force foot loading data and the kinematic and kinetic walking parameters demonstrating significant between-group differences ($p<0.05$) were explored using Pearson correlation coefficients. This test is commonly used to provide an index that reflects a quantitative measure of the strength and direction of a relationship between two variables and is based on the concept of covariance; whereby two sets of scores demonstrate similar patterns. With a strong relationship the deviation of each score from its mean (referred to as a moment) should be related (Portney and Watkins, 2000). Pearson's correlation was selected as this statistic is appropriate for use on continuous variables with underlying normal distributions on the interval or ratio scales (Portney and Watkins, 2000).

Interpretation of the relationship between the characteristics of foot loading and kinematic and kinetic walking patterns was conducted in accordance to Portney and Watkins (2000), whereby values >0.75 indicate a good to excellent relationship, values ranging from 0.5-0.75 imply a moderate-to-good relationship, those from 0.25-0.49 suggest a fair degree of relationship and correlations <0.25 indicate little or no relationship. In all cases, the accepted level of significance was set at $p<0.05$.

Where significant relationships were identified between normalised peak force foot loading data and lower limb kinematic and kinetic walking patterns in overweight and obese children, linear regression analysis was then undertaken to establish whether these relationships form a basis for prediction. Linear regression provides a powerful statistical approach for explaining and predicting quantifiable clinical outcomes (Portney and Watkins, 2000). Kinematic and kinetic variables that demonstrated a significant relationship with normalised peak force data were input into the regression model in a backward stepwise method. The backward elimination stepwise method begins by developing a full regression model using all selected independent variables. Then a t-test for significance is performed on each regression coefficient at a specified alpha level (i.e. $p<0.05$). The variable that is least significant, that is, the one with the largest p-value, is removed and the model is refitted. Each subsequent step removes the least significant variable in the model until all remaining variables have individual p-values smaller than the accepted level of significance (Howell, 2013).

Howell (2013) argued that backward selection is preferable to forward selection and stepwise regression because it is possible for a set of variables to have considerable predictive capability even though any subset of them does not. Forward selection and stepwise regression will fail to identify them, because as the variables don't predict well individually, they will never get to enter the model to have their joint behavior noticed. Backwards elimination starts with everything in the model, so their joint predictive capability will be seen (Harrell et al. 1996; Howell, 2013). In all cases, the accepted level of significance was set at $p<0.05$.

To assess the impact of multicollinearity on the regression models the variance inflation factor and its tolerance statistic were calculated. Multicollinearity is a common problem when estimating regression models; occurring when there are high correlations among predictor variables, leading to unreliable and unstable estimates of regression coefficients (Rogerson, 2001). The variance inflation factor (VIF) and its tolerance statistic are commonly used as an indicator of multicollinearity, assessing how much the variance of the estimated regression coefficient is *"inflated"* by the existence of correlation among the predictor variables in the model. The VIF should ideally be below 5 and the tolerance statistic above 0.2 (O'Brien, 2007). Any variables found to have a VIF above 5 and tolerance statistics below 0.2 were removed from the regression model to reduce multicollinearity.

CHAPTER FOUR: EVALUATING WITHIN- AND BETWEEN-SESSION RELIABILITY OF TEST PROTOCOLS

4.1 Introduction

Plantar pressure assessment and three-dimensional gait analysis in young children are widely used in both clinical and research settings to assess the biomechanical function of the foot and lower limb and detail the impact of pathology on movement and function. However, gait in young children is idiosyncratic and collection of reliable gait data is challenging (Lythgo et al. 2009). The reliability of plantar pressure and gait parameters are usually measured in a single test session (within-session) across two or more trials and in a test-retest comparison (between-session), where a sample of participants are subjected to an identical test on two separate occasions, keeping all testing conditions as constant as possible, to ensure that an individual, protocol or instrument is capable of measuring a variable with consistency (Portney and Watkins, 2000).

The within- and between-session reliability of three-dimensional lower limb gait measurements have been previously reported in children (Mackey et al. 2005; Quigley et al. 1997; Steinwender et al. 2000; Stephensen et al. 2008; Stolze et al. 1998; Thorpe et al. 2005). Young children typically displayed less characteristic gait patterns during repetitive movements, which could result in a lower reliability of temporal-spatial, kinematic and kinetic gait parameters. A number of other methodological sources contribute towards within- and between-session reliability of three-dimensional gait analysis data, including motion capture system accuracy, marker placement accuracy with respect to anatomical landmarks, soft-tissue artefact (i.e. movement of the skin, muscles and other tissue), thickness of subcutaneous fat, anthropometric measurements, walking speed, data processing techniques as well as subject fatigue, motivation and concentration (Baker, 2006; Della Croce et al. 2005; McGinley et al.

2009; Schwartz et al. 2004). However, very few studies have sought to investigate the reliability of protocols for the assessment of plantar pressure data in children.

This chapter determines the within- and between-session reliability of measurement protocols for the assessment of body mass status using BMI and skinfold measures, foot loading characteristics via plantar pressure assessment and lower limb temporal-spatial, kinematic and kinetic gait parameters via three-dimensional motion analysis, during barefoot level walking in a group of typically developing children, aged 7 to 11 years. It was hypothesised that the collection of reliable data was possible in children.

4.2 Methods

4.2.1 Participants

The method for the recruitment of schools and subjects, including inclusion and exclusion criteria has been outlined in section 3.3 (page 61).

Forty five children (mean age, mass, height, BMI-SDS score and body fat % of 9.00 ± 1.35 years, 32.61 ± 9.57kg, 1.37 ± 0.09m, 0.02 ± 1.60 and 17.52 ± 5.10% respectively) were recruited to assess the within- and between-session reliability of anthropometry using BMI and skinfold measures and foot loading via plantar pressure assessment.

Twelve children (9.75 ± 1.66 years, 45.54 ± 24.40kg, 146.7 ± 18.0cm, 1.24 ± 0.96 and 22.55 ± 4.66%) were recruited to assess the within- and between-session reliability of lower limb temporal-spatial, kinematic and kinetic gait parameters.

4.2.2 Experimental Procedures

Anthropometric, plantar pressure and temporal-spatial, kinematic and kinetic gait data was acquired according to the methods outlined in sections 3.4.1 (page 63), 3.4.2

(page 67) and 3.4.3 (page 71). Data from three trials were collected at both an initial and re-test session, with at least 48-hours and no more than 7-days between re-test.

4.2.3 Data Analysis

Within- and between-session reliability of the protocols was determined according to the methods described in section 3.5.1 (page 80).

4.3 Results

Within- and between session reliability of anthropometrical measures, foot loading characteristics and lower limb temporal-spatial, kinematic and kinetic gait parameters are summarised in Appendix 6 (Tables A4.1 to A4.13) (pages 213-218).

4.3.1 Anthropometrical Data

The within- and between-session reliability for anthropometric data is presented in Table A4.1 (page 215). Good within-session reliability was reported for all measures (ICCs: 0.90-0.99). The relative reliability between-sessions were also good for all the measures, as evidenced by ICCs of 0.96-0.99.

4.3.2 Plantar Pressure Assessment

Within-session measures of reliability are reported in Table A4.2 (page 216). The parameters demonstrated moderate-to-good reliability, with ICCs ranging from 0.69-0.93 for all variables across all segments of the foot except the 2nd-5th toes, which demonstrated poorer reliability (ICCs: 0.17-0.50). CoV ranged from 10.22-27.15% for peak pressure, 10.95-41.67% for peak force, 13.87-48.31% for pressure-time integrals and 13.37-56.08% for force-time integrals. In all cases the 2nd-5th toes demonstrated the greatest degree of variation within trials.

Between-session measures of reliability are reported in Table A4.3 (page 217). Mean difference between testing sessions were significant for peak pressure, peak force, pressure-time and force-time integrals at the 2nd-5th toes ($p<0.05$). Good between-session reliability (ICCs: >0.79) were reported for all variables across foot segments except the 2nd-5th toes which demonstrated moderate reliability (ICCs: 0.58-0.68). The CoV between-sessions demonstrated that the 2nd-5th toes (29.64-56.61%) demonstrated the greatest degree of variation across all plantar variables. Mean differences ranged from -6.17 ± 29.83 to 11.30 ± 18.79 kPa for peak pressure, -5.63 ± 3.13 to 5.73 ± 7.94 N for peak force, -4.18 ± 3.64 to -0.970 ± 7.74 kPa/sec for pressure-time integrals and -3.93 ± 3.57 to 5.67 ± 1.99 N/sec for force-time integrals.

4.3.3 Temporal-spatial, Kinematic and Kinetic Gait Analysis

No mean difference between test sessions was reported for any temporal-spatial, kinematic and kinetic parameter.

4.3.3.1 Temporal-spatial Parameters

Good within-session reliability was found for step length (ICCs: 0.86) and step width (ICCs: 0.85), whereas moderate reliability was found for velocity (ICCs: 0.66), cadence (ICCs: 0.66), single-support duration (ICCs: 0.71) and double-support duration (ICCs: 0.64) (Table A4.4, page 218). CoV were lower for velocity, cadence, step length and step width (4.43-7.82%) and higher for single-support (11.67%) and double-support duration (12.93%) (Table A4.4, page 218). Good between-session reliability (ICCs: 0.79-0.97) was reported for all the variables (Table A4.4, page 218).

4.3.3.2 Kinematic Parameters

4.3.3.2.1 Sagittal Plane

Good within-session reliability was demonstrated at both the knee (ICCs: 0.77-0.94) and ankle (ICCs: 0.76-0.91), whereas moderate-to-good within-session reliability was found at the hip (ICCs: 0.58-0.92) (Table A4.5, page 219) during the phases of IDS, SS, TDS and SW. Lowest ICCs values were reported for minimum (ICCs: 0.58) and maximum (ICCs: 0.63) hip angles during SW. Moderate-to-good between-session reliability was demonstrated at the knee (ICCs: 0.66-0.96) and ankle (ICCs: 0.58-0.98), whereas poor-to-moderate levels of reliability were reported at the hip (ICCs: 0.24-0.73) (Table A4.6, page 220). Values of ICCs were <0.5 for minimum hip angle during TDS (0.49) and maximum hip angle during SW (0.24). Mean differences ranged from -3.08 ± 3.64^0 to 3.73 ± 3.98^0, 3.61 ± 3.36^0 to 3.38 ± 4.91^0 and 3.64 ± 3.36^0 to 2.43 ± 2.35^0 at the hip, knee and ankle respectively (Table A4.6, page 220).

4.3.3.2.2 Frontal Plane

Good within-session reliability was demonstrated at the knee (ICCs: 0.76-0.93), whereas moderate-to-good levels of within-session reliability was reported at the hip (ICCs: 0.57-0.93) and ankle (ICCs: 0.73-0.93) (Table A4.5, page 219) during the phases of IDS, SS, TDS and SW. ICCs were lowest for the minimum hip angle during TDS (ICCs: 0.57). Moderate-to-good between-session reliability was found at the hip (ICCs: 0.69-0.95), knee (ICCs: 0.71-0.98) and ankle (ICCs: 0.56-0.96) (Table A4.7, page 221). ICCs values were lowest for the minimum ankle angle during SW (0.56). Mean differences ranged from -1.85 ± 2.71^0 to 3.17 ± 3.73^0, -0.83 ± 2.26^0 to 2.45 ± 4.36^0 and -1.38 ± 2.06^0 to 2.92 ± 2.88^0 at the hip, knee and ankle respectively (Table A4.7, page 221).

4.3.3.2.3 Transverse Plane

Moderate-to-good within-session reliability was found at the knee (ICCs: 0.56-0.83) and ankle (ICCs: 0.54-0.87); whereas poor-to-good reliability was reported at the hip (ICCs: 0.37-0.75) (Table A4.5, page 219) during the phases of IDS, SS, TDS and SW. Values of ICCs were <0.5 for maximum (0.49) and minimum (0.37) hip angles during SW. Large CoV were reported for the maximum hip angle during TDS (CoV: 36.69%). Poor-to-moderate levels of between-session reliability were found at the hip (ICCs: 0.33-0.67), knee (ICCs: 0.34-0.71) and ankle (ICCs: 0.37-0.74) (Table A4.8, page 222). Values of ICCs were <0.5 for maximum and minimum knee angles during IDS, maximum hip angle during SS, maximum and minimum hip and maximum knee angles during TDS and minimum knee angle during SW. Mean differences ranged from -3.72 ± 6.99^0 to 4.30 ± 4.84^0, -3.52 ± 5.66^0 to 2.51 ± 3.03^0 and -4.25 ± 4.84^0 to 2.35 ± 4.75^0 at the hip, knee and ankle respectively (Table A4.8, page 222).

4.3.3.3 Kinetic Parameters

4.3.3.3.1 Vertical Ground Reaction Force

Good within- (ICCs: 0.95-0.99) and between-session (ICCs: 0.88-0.93) reliability was found for the vertical ground reaction force data across the different phases of the gait cycle (Table A4.9, page 223). Between-session mean differences of -7.72 ± 6.43 N, -6.94 ± 6.77 N and -7.91 ± 9.83 N were reported during IDS, SS and TDS respectively (Table A4.9, page 223).

4.3.3.3.2 Sagittal Plane

Good within- (Table A4.10, page 224) and between-session (Table A4.11, page 225) reliability was demonstrated for all kinetic parameters at the hip, knee and ankle (ICCs: >0.75) during the phases of IDS, SS, TDS and SW. Mean differences ranged from -0.23 ± 0.30 Nm/kg to 0.22 ± 0.35 Nm/kg, -0.18 ± 0.24 Nm/kg to 0.07 ± 0.14 Nm/kg and -0.10 ± 0.05 Nm/kg to 0.09 ± 0.29 Nm/kg at the hip, knee and ankle respectively (Table A4.11, page 225).

4.3.3.3.3 Frontal Plane

Good within- (Table A4.10, page 224) and between-session (Table A4.12, page 226) reliability was demonstrated for all kinetic parameters at the hip, knee and ankle (ICCs: >0.75) during the phases of IDS, SS, TDS and SW. Mean differences ranged from -

0.09 ± 0.21 Nm/kg to 0.07 ± 0.21 Nm/kg, -0.12 ± 0.21 Nm/kg to 0.06 ± 0.10 Nm/kg and -0.03 ± 0.16 Nm/kg to 0.09 ± 0.17 Nm/kg at the hip, knee and ankle respectively (Table A4.12, page 226).

4.4.3.3.4 Transverse Plane

Good within-session reliability was found at the hip (ICCs: 0.76-0.91) and ankle (ICCs: 0.75-0.97), whereas moderate-to-good reliability was demonstrated at the knee (ICCs: 0.73-0.97) (Table A4.10, page 224) during the phases of IDS, SS, TDS and SW. Moderate-to-good between-session reliability was reported at the hip (ICCs: 0.57-0.84), knee (ICCs: 0.56-0.84) and ankle (ICCs: 0.60-0.91) (Table A4.13, page 227). Mean differences ranged from 0.04 ± 0.04 Nm/kg to 0.07 ± 0.04 Nm/kg, -0.06 ± 0.14 Nm/kg to 0.04 ± 0.03 Nm/kg and -0.07 ± 0.12 Nm/kg to 0.07 ± 0.19 Nm/kg at the hip, knee and ankle respectively (Table A4.13, page 227).

4.4 Discussion

This chapter aimed to determine the within- and between-session reliability of the measurement protocols for the assessment of body mass status, foot loading and lower limb temporal-spatial, kinematic and kinetic gait parameters, during barefoot level walking in a group of typically developing children, aged 7 to 11 years.

4.4.1 Anthropometrical Data

Good levels of within- and between-session reliability were reported for all measures of anthropometry as evidenced by ICCs of 0.95-0.99. These results are consistent with previous findings (Oza-Frank et al. 2012; WHO Multicentre Growth Reference Study Group, 2006) and demonstrated that the protocols were reliable. This data supports the research hypothesis and as such all methods will be adopted in studies two (Chapter Five, page 100) and three (Chapter Six, page 120).

4.4.2 Plantar Pressure Assessment

Moderate-to-good within- and between-session reliability was reported for all measures of foot loading across all segments of the foot except the 2nd-5th toes which reported poorer reliability. Analysis of the within- and between-session CoV showed a similar pattern to the ICCs in that the 2nd-5th toes demonstrated the greatest degree of variation for all parameters of foot loading. Additionally, assessment of systematic differences between sessions indicated that for all parameters of foot loading only the 2nd-5th toes exhibited a significant mean difference between sessions ($p<0.05$).

These results demonstrate that the protocols adopted in this study yield reliable pressure data in children, aged 7 to 11 years, during barefoot level walking, using the MatScan® (TekScan, USA) pressure platform, across all regions of the foot excluding the 2nd-5th toes. The results suggest that the participants walked in a repeatable manner and that foot loading was consistent across the platform except at the 2nd-5th toes. Repeated measurements at the 2nd-5th toes were associated with reduced reliability and increased variation during barefoot level walking and indicate that there may be limitations in isolating this small region of the foot. This data supports the research hypothesis; however, measurements at the 2nd-5th toes are deemed unreliable in the assessment of foot loading in children and will not be used during the between-group comparative work in study two (Chapter Five, page 100).

The findings at the 2nd-5th toes in this study are consistent with previous reports in adults (Gurney et al. 2008; Zammit et al. 2010). Although these results are of interest, direct comparison between studies is difficult due to differences in the participants, methodologies adopted and in the sensor technology used. The study by Gurney et al. (2008) assessed reliability using the Novel EMED® plantar pressure platform, in comparison to the TekScan MatScan® system used in this study. The methods used for segmental division of the foot vary between systems and can be subject to error resulting from the spatial resolution of the platform and anatomical knowledge of the observer's involved (Stebbins et al. 2005), as the Novel EMED® platform has a slightly higher spatial resolution of 2 sensors/cm^2 in comparison to 1.4 sensors/cm^2 of the TekScan MatScan® system. Consequently, although the collection of reliable foot loading data appears possible in children, the lower spatial resolution of the TekScan MatScan® system may limit the validity of this system in accurately being able to isolate small regions of the foot, such as the 2nd-5th toes and highlights the importance of the resolution of a system when assessing the plantar pressures in children with small foot sizes. This is in agreement with the work of Latour et al. (2011) and Urry and Wearing (2001) whom both commented that the lower reliability at the 2nd-5th toes may be due to limitations with sensor technology in isolating this small region of the foot, particularly in young children.

4.4.3 Temporal-spatial, Kinematic and Kinetic Gait Analysis

4.4.3.1 Temporal-spatial Parameters

Moderate-to-good within- and between-session reliability was reported in all temporal-spatial measures. These results demonstrate the protocols adopted in this study are suitable to yield reliable temporal-spatial data using the VICON (VICON 612, Oxford, UK) motion analysis system and suggest that the participants gait pattern and walking speed were consistent across repeated trials and test sessions. This data supports the research hypothesis and all temporal-spatial measures will be adopted for the between-group comparative work in study three (Chapter Six, page 120).

These results are in agreement with the earlier work of Stephensen et al. (2008) who reported moderate-to-excellent reliability (ICCs: 0.60-0.97) for the temporal-spatial gait parameters of velocity, cadence, stride length and stride width, as well as single-support and double support duration in a group of four healthy children.

4.4.3.2 Kinematic Parameters

Poor-to-good within and between-session reliability was reported in all sagittal, frontal and transverse plane kinematic parameters at the hip, knee and ankle during the phases of IDS, SS, TDS and SW. Within- and between-session CoV were higher at the hip in comparison to the knee and ankle and were greatest during SW across the three movement planes (Tables A4.5, page 210 and A4.6, page 211). Reduced mean ICCs and higher mean CoV (both within- and between-sessions) were also reported in the transverse plane when compared to the sagittal and frontal planes.

This data supports the research hypothesis, demonstrating that the protocols adopted in this study are suitable to yield reliable lower limb joint kinematic measures using the VICON (VICON 612, Oxford, UK) motion analysis system in children, aged 7 to 11 years, across the gait cycle and suggest lower limb joint kinematics were consistent across repeated trials and marker reapplication was consistent between test sessions. Consequently, all kinematic measures will be adopted for the between-group comparative work in study three (Chapter Six, page 120).

Repeated and re-test kinematic measures were less reliable and demonstrated increased variation at the hip, suggesting that the range of movement at this joint was less consistent during repeated trials and between test sessions. The findings at the hip are consistent with those previously reported in children (Stephensen et al. 2008) and indicate that this region may be subject to methodological error. Accurately identifying the hip and knee joint centres has been shown to significantly contribute towards measurement errors associated with this site (Schwartz et al. 2004) and highlights the importance of placing markers accurately (with respect to specific anatomical landmarks) and determining the location of the joint centres (in relation to these markers). Marker re-application error has also been shown to contribute to re-test kinematic error (McGinley et al. 2009). To minimise this, the markers on all the participants of this study were applied by the same person using a standardised protocol, however some re-application error is inevitable and the lower between-session ICC values at the hip suggests that differences in marker placement at the hip and knee joint centres influenced measurement accuracy. Kadaba et al. (1989) attributed errors in the reapplication of markers to be a major cause for variation in gait analysis data. It has also been suggested that measurement errors arise from various other methodological sources including variation in gait patterns and soft-tissue artefact about the bones of the lower limb, which is perhaps most abundant in relation to the profile of the hip (Baker, 2006).

Lower ICCs and higher CoV at the hip, knee and ankle were demonstrated during the SW phase of the gait cycle across all three movement planes; indicating that the kinematics of the lower limb were less consistent during this phase. To the author's knowledge, this study represents the first to consider the reliability of lower limb joint kinematic data during phases of the gait cycle in children and as such comparative data is lacking. Kadaba et al. (1989) reported reduced reliability, as attested by lower CMCs, in the SW phase kinematics in a sample of 40 normal adult participants. The authors attributed this to variations in the estimation of velocity and acceleration of limb segments from marker position data; however these results would benefit from further analysis in a larger cohort of children.

Lower ICCs and higher CoV were also reported for the transverse plane motions at the hip, knee and ankle. These results are consistent with those previously reported in children (Mackey et al. 2005; Steinwender et al. 2000) where higher reliability was reported in the joint kinematics of the hip, knee and ankle in the sagittal and frontal planes indicating that inconsistencies in the pattern of walking in children are reflected more greatly in transverse plane motions. Finally, mean differences were small between test sessions, ranging from -4.56-5.52^0 at the hip, knee and ankle respectively across the three movement planes. It has been suggested that in most common clinical situations measurement errors of 2-5^0 are widely considered acceptable for the interpretation of repeated measurements in gait studies (Manca et al. 2010; McGinley et al. 2009; Noehren et al. 2010).

4.4.3.3 Kinetic Parameters

Moderate-to-good within- and between-session reliability was reported for all kinetic parameters at the hip, knee and ankle across the three movement planes. Within and between-session mean ICCs and CoV were lower and higher respectively in the transverse plane when compared to the sagittal and frontal planes. This data supports the research hypothesis and indicates that the protocols adopted in this study are suitable to yield reliable kinetic data for the lower limb using the VICON (VICON 612, Oxford, UK) motion analysis system across multiple phases of the gait cycle in children. Consequently, all vertical ground reaction force data as well as kinetic measures will be adopted for the between-group comparative work in study three (Chapter Six, page 120).

These findings parallel those of Stephensen et al. (2008) who reported excellent levels of reliability for ground reaction force and sagittal plane joint kinetic data at the hip, knee and ankle in children. Similarly, Steinwender et al. (2000) reported excellent within- and between-session reliability in sagittal plane joint kinetic data at the hip, knee and ankle and in frontal plane data at the hip. Neither author reported data in the transverse plane. Quigley et al. (1997) also reported moderate-to-good retest ICCs at the hip, knee and ankle in the sagittal, frontal and transverse planes. These results reinforce those of this study and suggest that ground reaction force and joint kinetics at the hip, knee and ankle exhibit acceptable within- and between-session reliability. The work by Quigley et al. (1997) also identified reduced reliability in the transverse plane, the results of which are consistent with those in this study indicating that inconsistencies in the kinetic patterns of walking in children are reflected more greatly in transverse plane motions. Variability in kinetic data may also be attributed to system (calculation of external joint moments) and measurement error (anthropometric data), physiological variability and the flexibility of individual muscles as they adapt to produce the same kinematic pattern (Ferber et al. 2002; Winter, 1984).

4.5 Chapter Summary

This chapter was designed to explore the within- and between-session reliability of the measurement protocols for the assessment of anthropometry, foot loading characteristics and lower limb temporal-spatial, kinematic and kinetic gait parameters in a group of typically developing children, aged 7 to 11 years. The results from this chapter demonstrate:

- Measurements used for the assessment of body mass status were reliable.
- Plantar pressure assessment was reliable across all regions of the foot, excluding the 2nd-5th toes.
- Reliable temporal-spatial gait data.
- Reliable sagittal, frontal and transverse plane lower limb joint kinematic and kinetic data during IDS, SS, TDS and SW.

This work provides evidence as to the reliability of anthropometric measures, plantar pressure assessment and lower limb temporal-spatial, kinematic and kinetic gait parameters in children. Evidence has emerged with regards the impact of obesity on the biomechanical function of the paediatric foot and with regards the impact of obesity on the temporal-spatial, kinematic and kinetic biomechanical function of the entire lower limb in children. The following chapters will look to determine the impact of overweight and obesity on plantar foot loading characteristics and lower limb temporal-spatial, kinematics and kinetics walking patterns in children, as well as investigate the relationship between plantar foot loading and the biomechanics of the lower limb.

CHAPTER FIVE: COMPARISON OF FOOT LOADING PATTERNS IN OBESE, OVERWEIGHT AND NORMAL WEIGHT CHILDREN

5.1 Introduction

Evaluation of plantar foot loading is important to determine if obesity undermines the integrity of the foot as a weight bearing structure. Childhood obesity has been reported to be a risk factor for development of musculoskeletal pathologies affecting the lower limb leading to altered foot loading, the impact of which has been discussed in section 2.3.2.5 (page 33). However, due to variations with the classification of obesity across studies, use of different pressure measurement technology, inconsistencies with protocols, differences in definition of foot segment(s) and lack of standardisation and reporting of plantar variables conclusions on the impact of obesity on the paediatric foot are still lacking. Furthermore, it is yet undetermined whether overweight children display similar changes in plantar foot loading as their obese counterparts. Further work is essential as early prevention and intervention will be key to mitigating against health co-morbidities associated with childhood obesity.

This chapter sought to determine the impact of overweight and obesity on the plantar foot loading characteristics of children, aged 7 to 11 years, during level walking. It was hypothesised that obese and overweight children would display increased levels of peak plantar pressure and force as well as increased levels of normalised force across the plantar surface of the foot in comparison to normal weight children. It was also hypothesised that obese and overweight children would display greater pressure-time and force-time integrals when compared to their normal weight peers.

5.2 Methods

5.2.1 Participants

The method for the recruitment of schools and participants, including inclusion and exclusion criteria has been outlined in section 3.3 (page 61).

100 participants were recruited to determine plantar foot loading characteristics in children who were obese (N = 22), overweight (N = 22) and normal weight (N = 56) during barefoot level walking. Participants were classified according to their BMI-SDS as outlined in section 3.4.1.6 (page 66). Participant characteristics, including gait velocity, are presented in Table 5.1.

Table 5.1. Anthropometric data (Mean ± SD) for the obese (N = 22), overweight (N = 22) and normal weight (N = 56) children

	Total (N=100)	**Obese Children**	**Overweight Children**	**Normal Weight Children**
Gender (M/F)	62/38	15/7	16/6	31/25
Age (years)	9.39 ± 1.65	9.95 ± 1.56	9.41 ± 1.74	9.16 ± 1.56
Body Mass (kg)	38.18 ± 14.42	55.75 ± 15.84	39.91 ± 8.23ł	30.59 ± 8.14*†
Stature (m)	1.48 ± 0.13	1.50 ± 0.14	1.48 ± 0.12	1.45 ± 0.10
BMI (kg/m^2)	18.29 ± 4.05	24.16 ± 3.14	19.17 ± 1.28ł	15.63 ± 2.04*†
BMI-SDS	0.47 ± 1.55	2.39 ± 0.49	1.30 ± 0.15ł	-0.62 ± 1.25*†
Gait Velocity (m/sec)	1.08 ± 0.49	1.06 ± 0.35	1.10 ± 0.14	1.12 ± 0.10

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

ł denotes a significant difference between obese and overweight children ($p<0.05$)

5.2.2 Experimental Procedures

Anthropometrical and plantar foot loading data was acquired according to the methods outlined in sections 3.4.1 (page 63) and 3.4.2 (page 67) respectively.

5.2.3 Data Analysis

A comparison of the anthropometric and plantar foot loading characteristics in the identified population was performed according to the methods described in section 3.5.2 (page 81). To help to characterise differences in the plantar foot loading characteristics in obese, overweight and normal weight children cluster analysis was performed on the data according to the methods described in section 3.5.3 (page 82).

5.3 Results

5.3.1 Anthropometric Characteristics

A one-way Analysis of Variance Test (ANOVA) revealed significant differences in body mass ($F_{(2,99)} = 27.10$, $p<0.05$), BMI ($F_{(2,99)} = 77.68$, $p<0.05$) and BMI-SDS ($F_{(2,99)} = 88.92$, $p<0.05$) between the three groups. Post-hoc analysis revealed that obese participants have a significantly greater body mass, BMI and BMI-SDS in comparison to the overweight and normal weight ($p<0.05$) children. The overweight children also demonstrated a significantly greater body mass, BMI and BMI-SDS in comparison to the normal weight participants ($p<0.05$).

5.3.2 Plantar Pressure Assessment

5.3.2.1 Peak Pressure and Peak Force

Descriptive data for the measures of peak pressure (kPa), absolute peak force (N) and normalised peak force (N/kg) in the obese, overweight and normal weight participants is summarised in Table 5.2 (page 107). A one-way ANOVA revealed significant group differences for peak pressure at the LH ($F_{(2,99)} = 2.25$, $p<0.05$), MID ($F_{(2,99)} = 9.64$, $p<0.05$) and 2-5MTPJ ($F_{(2,99)} = 10.26$, $p<0.05$) and for absolute peak force at the LH ($F_{(2,99)} = 2.39$, $p<0.05$), MH ($F_{(2,99)} = 3.22$, $p<0.05$), MID ($F_{(2,99)} = 9.14$, $p<0.05$) and 2-5MTPJ ($F_{(2,99)} = 9.78$, $p<0.05$) (Table 5.2, page 107).

Post-hoc analysis revealed significant group differences were located at the MID and 2-5MTPJ ($p<0.05$) between the overweight and normal weight children, where peak pressures and peak forces were higher for the overweight group (Table 5.2, page 107). Significant group differences for peak pressure ($p<0.05$) at the LH, MID and 2-5MTPJ were found between the obese and normal weight children (Table 5.2, page 107). Significant group differences for peak force ($p<0.05$) at the LH, MH, MID and 2-5MTPJ regions in comparison to the normal weight children were also found (Table 5.2, page 107). All values were higher for the obese children. In contrast to the above findings, the normal weight children demonstrated increased loading at the 1MTPJ and HAL in comparison to both the obese and overweight children although no significant group differences were shown to occur (Table 5.2, page 107).

Differences in peak force data were largely eliminated once normalised to body mass. However the results at the MID ($F_{(2,99)} = 37.62$, $p<0.05$) and 2-5MTPJ ($F_{(2,99)} = 7.88$, $p<0.05$) remained, with the children who were overweight and obese demonstrating increased loading at these sites (Table 5.2, page 107). Post-hoc analysis revealed significant group differences ($p<0.05$) between the overweight and obese participants in comparison to the normal weight children at both these regions of the foot.

5.3.2.2 Pressure-time and Force-time Integrals

Temporal characteristics of foot loading for the groups are summarised in Table 5.3 (page 108). Significant group effects at the LH ($F_{(2,99)} = 9.48$, $p<0.05$), MH ($F_{(2,99)} = 7.42$, $p<0.05$), MID ($F_{(2,99)} = 14.23$, $p<0.05$) and 2-5MTPJ ($F_{(2,99)} = 8.13$, $p<0.05$) for pressure-time integral data were identified and for force-time integral data at the LH ($F_{(2,99)} = 20.25$, $p<0.05$), MH ($F_{(2,99)} = 10.36$, $p<0.05$), MID ($F_{(2,99)} = 9.77$, $p<0.05$) and 2-5MTPJ ($F_{(2,99)} = 11.45$, $p<0.05$) (Table 5.3, page 108).

Elevated pressure-time and force-time integrals for the overweight and obese children were found (Table 5.3, page 108). Significant group differences ($p<0.05$) at the MID and 2-5MTPJ between children who were overweight and normal weight were found (Table 5.3, page 108). Significant group differences ($p<0.05$) were also found at the LH, MH, MID and 2-5MTPJ when comparing children who were obese and normal weight participants (Table 5.3, page 108). Pressure-time and force-time integrals at the 1MTPJ and HAL were higher in the normal weight participants when compared to both the obese and overweight children; however, no significant group differences were shown to occur (Table 5.3, page 108).

5.3.3 Cluster Analysis

Hierarchical cluster analysis identified two clusters for peak pressure, normalised peak force, pressure-time and force-time integral data across the six regions of the foot in the obese, overweight and normal weight children. Participants were then assigned to one of the two heterogeneous clusters through non-hierarchical (K-means) cluster analysis. The profiles of each cluster were described by their cluster centres for the characteristics of foot loading. Cluster One (C1) contained 61 participants, with cluster two (C2) containing the remaining 39. The majority of normal weight children (N = 53/56) formed C1 with the majority of obese (N = 19/22) and overweight (N = 17/22) children forming C2. Thus, the frequency of participants forming C1 were 94.6% normal weight, 22.7% overweight and 13.6% obese in comparison to 5.4% normal weight, 77.3% overweight and 86.4% obese in C2. The mean ± SD of the cluster centres for the characteristics of plantar foot loading in C1 and C2 are presented in Table 5.4 (page 110).

Further analysis (ANOVA) of the mean cluster centres identified significant differences between the two clusters ($p<0.05$) for the variables of peak pressure at the LH ($F_{(1,99)} = 37.32$, $p<0.05$), MH ($F_{(1,99)} = 41.54$, $p<0.05$), MID ($F_{(1,99)} = 11.63$, $p<0.05$) and 2-5MTPJ

($F_{(1,99)}$ = 105.60, $p<0.05$); pressure-time integrals at the LH ($F_{(1,99)}$ = 65.31, $p<0.05$), MH ($F_{(1,99)}$ = 86.72, $p<0.05$), MID ($F_{(1,99)}$ = 17.62, $p<0.05$) and 2-5MTPJ ($F_{(1,99)}$ = 95.75, $p<0.05$) and force-time integrals at the LH ($F_{(1,99)}$ = 49.17, $p<0.05$), MH ($F_{(1,99)}$ = 47.23, $p<0.05$), MID ($F_{(1,99)}$ = 11.49, $p<0.05$) and 2-5MTPJ ($F_{(1,99)}$ = 84.11, $p<0.05$) (Table 5.4, page 110). Significant differences between the two clusters ($p<0.05$) were also identified for normalised peak force data at the MID ($F_{(1,99)}$ = 9.92, $p<0.05$) and 2-5MTPJ ($F_{(1,99)}$ = 111.16, $p<0.05$) (Table 5.4, page 110). In all cases values were higher for C2. In contrast, mean cluster centres were higher for all variables of plantar foot loading at the 1MTPJ and HAL for the participants in C1 although no significant group differences were reported (Table 5.4, page 110).

Visual inspection of the dendrogram (Figure 5.1, page 109) offers a similar interpretation of the results. As previously discussed (Section 3.5.3, page 82), the Y-axis (vertical) of the dendrogram represents individual participants, with the number coinciding with the entry of their data into SPSS. The X-axis represents the size of the coefficient at which individuals are clustered, with a low distance coefficient indicating a greater level of similarity between participants. The dendrogram also depicts that clustering occurred across multiple levels. It appears that participants numbered 55, 100, 65, 72, 75, 27, 61 and 33 formed a cluster at the first level of hierarchical clustering (Figure 5.1, page 109). Numerous other clusters were formed at this level, including participants numbered 6, 56, 46, 49 and 30 as well as participants numbered 40, 57 and 22 (Figure 5.1, page 109). This process continues for the remaining participants numbered along the Y-axis. This first level of clustering indicates the participants within each cluster are more similar to other cluster group that may join at a higher level. At the second level of clustering, the first three clustered group identified above are then connected, indicating a level of similarity between these three clustered groups (Figure 5.1, page 109). This process continues until the ninth level where two cluster groups emerge, with participants numbered 55-39 (along the Y-axis) forming one cluster (N=76) and participants numbered 2-9 forming a second cluster (N=24) (Figure 5.1, page 109). Although the number of participants in each cluster is different to the results from the non-hierarchical (K-means) cluster analysis, cluster one still contained a majority of normal weight children (N = 55/56) with the majority of obese (N = 14/22) children being in cluster two. In contrast the majority of overweight children (N=13/22) were now in cluster 1. Furthermore, clustering at the ninth level occurs at a high distance coefficient, confirming that some participants may have been clustered even though they are much less alike. Finally, a tenth level of clustering was also evident, connecting the two cluster identified at the ninth level, indicating that some participants who joined the two clusters at a higher level might be suitable to fall into either of the two clusters.

Table 5.2. Summary of the dynamic peak pressure (kPa), peak force (N) and normalised force (N/kg) data for the obese (N = 22), overweight (N = 22) and normal weight children (N = 56) (Mean ± SD of three trials)

	Mean of three trials								
	Peak Pressure (kPa)			Peak Force (N)			Normalised Force (N/kg)		
Region	**Obese**	**Overweight**	**Normal weight**	**Obese**	**Overweight**	**Normal weight**	**Obese**	**Overweight**	**Normal weight**
Lateral heel	289.26 ± 79.73	249.85 ± 55.22	221.78 ± 85.15*	899.58 ± 217.29	762.05 ± 191.68	641.28 ± 168.98*	1.64 ± 0.40	1.95 ± 0.49	2.04 ± 0.56
Medial heel	269.02 ± 81.9	236.11 ± 54.53	220.08 ± 92.56	782.81 ± 232.05	655.43 ± 122.75	595.24 ± 242.30*	1.43 ± 0.42	1.67 ± 0.31	1.98 ± 0.81
Midfoot	110.88 ± 47.92	95.23 ± 52.75	58.33 ± 38.97*†	367.16 ± 121.76	318.72 ± 138.65	173.59 ± 85.01*†	0.67 ± 0.22	0.65 ± 0.25	0.48 ± 0.28*†
1MTPJ	178.01 ± 19.94	185.39 ± 82.03	194.41 ± 59.82	511.46 ± 208.44	507.69 ± 184.64	515.21 ± 135.82	0.96 ± 0.38	1.17 ± 0.47	1.22 ± 0.45
2-5MTPJ	277.49 ± 91.08	244.85 ± 80.79	198.41 ± 54.55*†	1034.98 ± 358.77	946.38 ± 253.83	573.16 ± 143.37*†	2.18 ± 0.47	2.16 ± 0.65	1.81 ± 0.48*†
Hallux	211.01 ± 19.94	214.19 ± 79.77	216.47 ± 86.08	673.72 ± 197.07	635.72 ± 206.80	696.36 ± 178.51	0.92 ± 0.38	1.09 ± 0.50	2.32 ± 0.59

* denotes a significant difference between obese and normal weight children (p<0.05)

† denotes a significant difference between overweight and normal weight children (p<0.05)

Table 5.3. Summary of the pressure-time integral (kPa/s) and force-time integral (N/s) data for the obese (N = 22), overweight (N = 22) and normal weight children (N = 56) (Mean ± SD of three trials)

	Mean of three trials					
	Pressure-time integral (kPa/s)			**Force-time integral (N/s)**		
Region	**Obese**	**Overweight**	**Normal weight**	**Obese**	**Overweight**	**Normal weight**
Lateral heel	46.90 ± 22.47	35.26 ± 11.64	29.14 ± 11.49*	743.46 ± 379.16	426.80 ± 169.88	388.24 ± 94.42*
Medial heel	46.59 ± 26.12	34.84 ± 12.19	29.48 ± 10.57*	615.32 ± 360.77	364.62 ± 142.79	243.76 ± 57.94*
Midfoot	21.80 ± 8.71	18.93 ± 9.82	10.02 ± 6.22*†	594.88 ± 322.18	432.58 ± 267.47	115.07 ± 97.33*†
1MTPJ	38.70 ± 14.96	32.09 ± 13.09	40.89 ± 17.56	220.29 ± 185.41	262.62 ± 175.47	277.55 ± 147.37
2-5MTPJ	46.74 ± 15.26	44.33 ± 16.42	33.83 ± 9.47*†	994.41 ± 667.49	625.98 ± 431.39	460.40 ± 153.04*†
Hallux	31.41 ± 31.42	30.75 ± 13.47	32.18 ± 19.64	163.71 ± 131.67	172.94 ± 135.34	234.97 ± 134.36

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

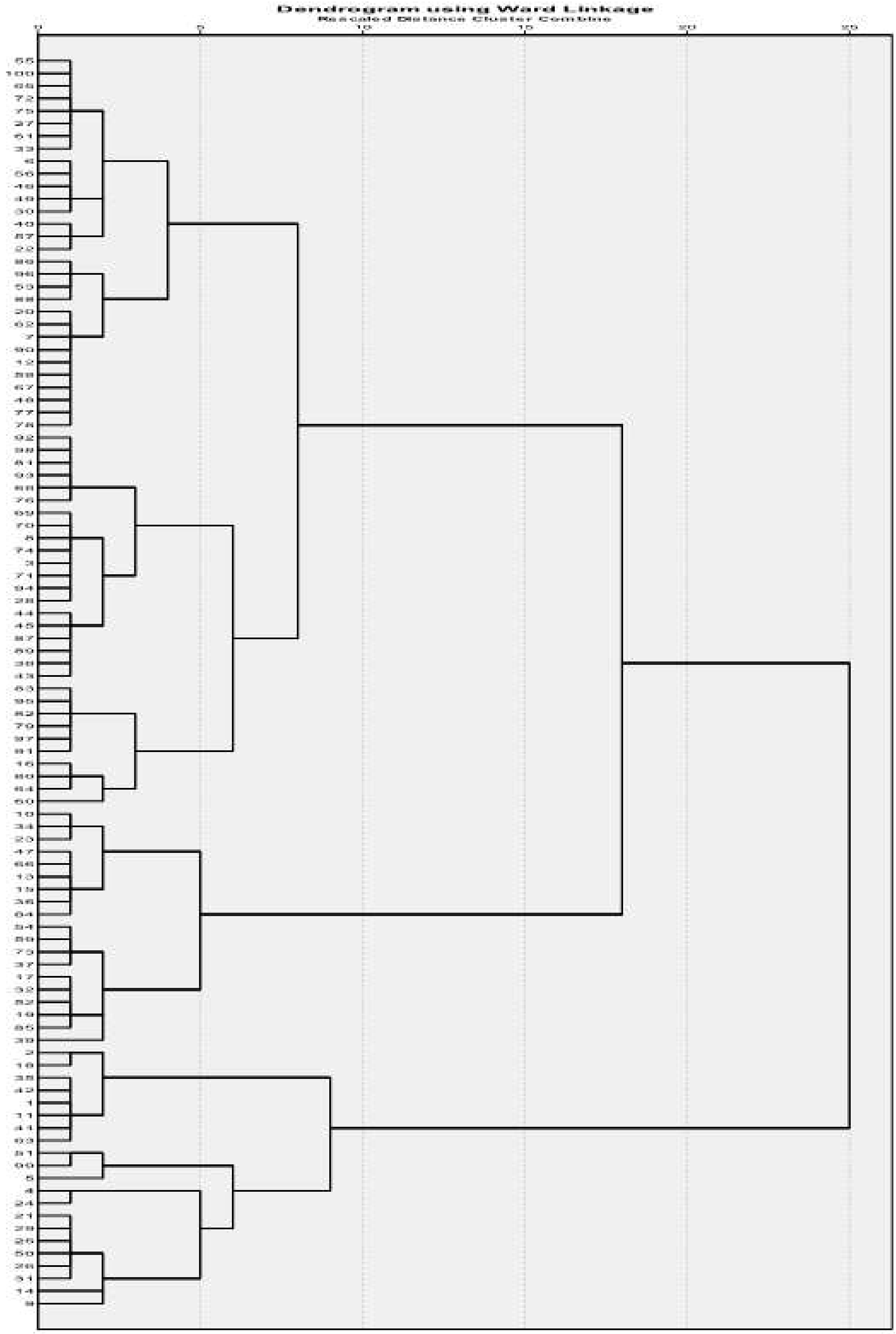


Figure 5.1. Dendrogram identifying the number of clusters based upon the foot loading characteristics of peak pressure, normalised peak force, pressure-time integrals and force-time integrals for obese (N = 22), overweight (N = 22) and normal weight children (N = 56)

Table 5.4. Summary of the mean cluster centres (mean ± SD) for the variables of peak pressure, normalised peak force, pressure-time integrals and force-time integrals in C1 and C2

	Cluster One (N=61)	**Cluster Two (N=39)**
Participants (N)		
Obese Children	3	19
Overweight Children	5	17
Normal Weight Children	53	3
Peak Pressure (kPa)		
Lateral Heel	228.40 ± 85.25	321.60 ± 37.32*
Medial Heel	207.80 ± 52.36	305.84 ± 54.96*
Midfoot	69.73 ± 32.77	108.35 ± 11.63*
1st metatarsal	19.49 ± 58.02	162.21 ± 33.87
2nd-5th Metatarsal	173.18 ± 18.93	322.46 ± 105.61*
Hallux	208.97 ± 18.10	200.08 ± 18.27
Normalised Force (N/kg)		
Lateral Heel	1.97 ± 0.45	1.91 ± 0.53
Medial Heel	1.79 ± 0.37	1.76 ± 0.56
Midfoot	0.58 ± 0.24	0.66 ± 0.27*
1st metatarsal	1.99 ± 0.43	1.92 ± 0.46
2nd-5th Metatarsal	1.53 ± 0.56	1.98 ± 0.57*
Hallux	1.59 ± 0.44	1.63 ± 0.55
Pressure-time integral (kPa/s)		
Lateral Heel	26.01 ± 11.57	51.56 ± 17.06*
Medial Heel	25.85 ± 11.38	55.02 ± 19.16*
Midfoot	15.16 ± 8.02	24.75 ± 10.37*
1st metatarsal	42.61 ± 15.33	35.33 ± 14.03
2nd-5th Metatarsal	28.41 ± 12.95	56.05 ± 15.84*
Hallux	39.63 ± 16.56	32.77 ± 22.45
Force-time integral (N/s)		
Lateral Heel	38.66 ± 17.15	82.46 ± 49.17*
Medial Heel	25.46 ± 16.37	59.88 ± 47.23*
Midfoot	25.66 ± 21.90	49.31 ± 11.49*
1st metatarsal	51.99 ± 16.42	38.91 ± 7.06
2nd-5th Metatarsal	58.06 ± 27.26	141.55 ± 84.12*
Hallux	38.08 ± 14.35	23.81 ± 5.64

* denotes a significant difference between cluster one and cluster two ($p<0.05$)

5.4 Discussion

This chapter aimed to determine the impact of overweight and obesity on the plantar foot loading characteristics of children, aged 7 to 11 years, during level walking. The following discussion will explore the results from this phase of work in two parts: 1) The comparative analysis of plantar foot loading characteristics in obese, overweight and normal weight children; and 2) The use of cluster analysis to characterise differences in the plantar foot loading characteristics in the identified population.

5.4.1 Comparative Analysis of Plantar Foot Loading Characteristics in Obese, Overweight and Normal Weight Children

It was hypothesised that obese and overweight children will display increased levels of peak plantar pressure and force as well as increased levels of normalised force across the plantar surface of the foot in comparison to normal weight children. It was also hypothesised that obese and overweight children will display greater pressure-time and force-time integrals when compared to their normal weight peers. This data supports the research hypothesis presented.

The findings identified that that children aged 7 to 11 years, who were overweight, displayed marked differences in plantar foot loading, when compared with normal weight children. Overweight children generated significantly greater peak pressures and peak forces at the MID and 2-5MTPJ regions of the foot, a trend that was similar to the obese children with significant differences also found at the LH and MH in comparison to the normal weight children. Overweight children also generated significantly increased pressure-time and force-time integrals under the MID and 2-5MTPJ. Again, a similar trend was found for the obese children with significant differences also reported at the LH and MH. The results at the 1MTPJ and HAL differ to those described above with the normal weight children demonstrating increased loading characteristics at these discrete regions of the foot.

Significant differences in the loading characteristics of overweight and obese children in this present study are consistent with previous research (Dowling et al. 2001, 2004; Mickle et al. 2006; Yan et al. 2013). Previous findings identified significantly higher peak pressures, peak forces, pressure-time integrals and force-time integrals at the plantar heel, MID and 2-5MTPJ when comparing obese to non-obese children. However, utilising the current evidence to form a consensus on the impact of obesity and inform current care provision for children is challenging due to variations with the classification of obesity across studies, use of different pressure measurement technology, inconsistencies with protocols, differences in definition of foot segment(s) and lack of standardisation and reporting of plantar variables. Additionally, previous studies have limited comparisons to children who are obese and normal weight and the findings from this study demonstrated that children who are overweight display similar plantar foot loading characteristics to children who are obese, with significantly increased peak and temporal loading at the MID and 2-5MTPJ. These results indicate that changes in a child's foot loading (associated with obesity), occur earlier than previously reported and may be associated with a smaller increase in body mass than first thought. These findings suggest a change in the biomechanical function of the foot, in regards to altered loading patterns and support the view that children who are overweight and obese could be at risk of developing foot discomfort as a consequence of the increased pressures and forces acting upon the immature musculoskeletal structure of the paediatric foot.

Elevated and prolonged patterns of foot loading at the MID in both the overweight and obese groups suggest increased ground contact during walking. This could be a result of excessive adipose tissue around the medial foot leading to increased loading, although it has been demonstrated that obese children do not have greater adipose tissue than non-obese children (Mickle et al. 2006). Additionally, recent work has reported low correlations between medial midfoot plantar pressures and midfoot plantar fat pad thickness (Riddiford-Harland et al. 2011). An alternative suggestion for increased loading at these sites may be explained by a change in the biomechanical function of the foot. There is a common view that obese children have a pes planus foot posture and the loading patterns demonstrated in this study were consistent with previous literature (Dowling et al. 2001; Mauch et al. 2008; Mickle et al 2006; Riddiford-Harland et al. 2011; Yan et al. 2013). In addition, Yan and colleagues (2013) citing the work of D'Aout et al. (2008) stated that the foot is pronating when the loading (force and pressure) is higher under the medial region as demonstrated by both children who were overweight and obese in the present study. The findings were significant for the children who were obese compared to the normal weight children but not for the children who were overweight, although the trend in the data suggested an increase.

When peak force was normalised to body mass a significant increase at the MID and 2-5MTPJ in the obese and overweight children was found. Thus, when normalised to body mass the obese and overweight participants still demonstrated a significant change in plantar foot loading at these sites. This reiterates the suggestion that there is an underlying difference in the biomechanics of foot loading in these children and indicates an elevated level of loading applied to the soft-tissue and joint structures at these regions. These findings are consistent with the view that children who are obese are at an increased risk of developing foot discomfort and/or pathology (Taylor et al. 2002; Wearing et al. 2006), as a consequence of the increased pressures and forces acting upon the immature musculoskeletal structure of the paediatric foot. Interestingly, no significant group differences were reported for peak pressure, peak and normalised force, pressure-time integral and force-time integral values at the 1MTPJ and HAL. The trend is our data suggested a decrease in loading which may further support the view that overweight and obesity affects the biomechanical function of the paediatric foot and highlights the potential for intervention to encourage a more medial loading pattern at the forefoot to alleviate increased pressures and forces at the 2-5MTPJ.

Emerging from this work is the view that earlier intervention and consideration of the foot in children who are overweight may be required to mitigate against further health co-morbidities. Although speculative, previous research has indicated that children who generated higher peak loading characteristics on the plantar surface of the foot were more likely to suffer pain and discomfort in their feet (Mickle et al. 2011). Recent research has also reported foot pain to be the most common symptom reported by children who are obese (O'Malley et al. 2012). Foot discomfort and/or pain associated with increase plantar foot loading and increased tissue stress may have additional complications in-so-much that it may hinder their participation in physical activity as weight bearing activities can become difficult if not appropriately designed to account for these functional changes (Mickle et al. 2011).

The peak loading characteristics in the obese, overweight and normal weight children are useful to distinguish between normal and increased loading patterns on the plantar aspect of the foot, as demonstrated by the increases in peak pressures and forces at the LH, MH, MID and 2-5MTPJ in the overweight and obese participants. This was also accompanied by increased pressure-time and force-time integrals at these regions, serving to increase the culmative effects of these loads during walking. This work helps to advance our knowledge as to the effects of overweight and obesity on the plantar foot loading characteristics of children aged 7 to 11 years. However, Hlair et al. (1998) cited by Mauch et al. (2008) noted that differences in the characteristics of foot loading do not necessarily infer altered function and advocated the use of more advanced statistical approaches to characterise foot function, with the application of cluster analysis.

5.4.2 Cluster Analysis of Plantar Foot Loading Characteristics in Obese, Overweight and Normal Weight Children

Differences in the plantar foot loading characteristics of obese, overweight and normal weight children were confirmed through using cluster analysis. Hierarchical cluster analysis identified two heterogeneous clusters (C1 and C2) with respect to the variables of peak pressure, normalised peak force, pressure-time integrals and force-time integrals across the six regions of the foot. Non-hierarchical cluster analysis revealed the selection of participants into each cluster appeared to be influenced by body mass with 94.6% of the normal weight children forming C1 in contrast to 86.4% and 77.3% for the obese and overweight children respectively who formed C2. Further analysis identified those participants in C2 generated significantly greater peak pressure, pressure-time integral and force-time integral values at the LH, MH, MID and 2-5MTPJ and normalised peak force values at the MID and 2-5MTPJ. In contrast, plantar foot loading at the 1MTPJ and HAL were greater for the participants in C1. This data supports the research hypothesis and reinforces the suggestion of a change in the biomechanical function of the paediatric foot with regards the plantar foot loading patterns of obese and overweight children, indicative of elevated levels of loading acting upon the soft-tissue and joint structures of the heel, MID and 2-5MTPJ. Furthermore, these results support the view that significant increases in the plantar foot loading characteristics occur with smaller gains in body mass than first thought with the view that children who are overweight and obese are at an increased risk of developing foot discomfort and/or pathology.

Analysis of the dendrogram offers a slightly different interpretation of the results and although two clusters did emerge with the majority of normal weight children (98.2%) forming cluster 1 and obese children (63.6%) forming cluster 2, the majority of overweight children now appeared to reside in cluster 1 (59.1%). In addition, two clusters did not emerge until the 9th level of clustering, indicating that some participants may have been clustered even though they are much less alike (Garson, 2012). However, due to the absence of agreed criterion for the interpretation of distance coefficients and statistically acceptable level of clustering it is difficult to comment upon the validity of the emerging clusters derived from this analysis. This is supported by Garson (2012) who argues that a set of clusters can emerge from a data set regardless of whether there is an actual grouping of individual cases, with further work required to establish statistically acceptable levels of clustering and distance coefficients to improve the validity around the reporting of cluster analysis. Furthermore, the dendrogram appears to indicate a link between the two emerging clusters at a higher level, suggesting that some participants who joined the two clusters at later levels might be suitable to fall into either cluster (Garson, 2012), which may explain the differences in the number of obese, overweight and normal weight children that fall into each cluster when comparing the hierarchical and non-hierarchical cluster analysis to the dendrogram. As a result, further work investigating the use of cluster analysis in identifying groups of children with similar foot loading characteristics is warranted.

To the author's knowledge, this study represents the first of its kind to identify alterations in the characteristics of plantar foot loading in obese, overweight and normal weight children using cluster analysis and as such comparative findings are lacking. The results from the hierarchical and non-hierarchical cluster analysis identified that during walking the majority of overweight and obese children (C2) load the plantar surface of their foot differently in comparison to normal weight children with two distinct patterns of foot loading being identified. When data normalised to body mass was considered participants in C2 demonstrated increased loading at the MID and 2-5MTPJ alongside reduced plantar loading at the heel, 1MTPJ and HAL. Elevated and prolonged patterns of plantar foot loading at the MID suggests a change in the biomechanical function of the foot, indicative of a flatter (planus) foot type which could imply a lowered medial-longitudinal arch (MLA). A flatter foot type is a common musculoskeletal co-morbidity associated with childhood obesity (Chen et al. 2011; Pfeiffer et al. 2006; Villarroya et al. 2009).

Mauch et al. (2008) investigated the influence of body mass on the 3D foot shape of children, aged 2-14 years (N = 2887) using cluster analysis. The authors reported differences among foot types and children's BMI. Significantly higher values for BMI were evident in children with flat feet characterised by a flattening of the MLA. In addition, the increased loading of the 2nd-5th metatarsals highlights the importance of this region as a weight-bearing structure during push-off (Jacob, 2001). A limited range of motion at the 2nd-5th metatarsal and hypermobile 1st metatarsal that is unable to provide the necessary support during propulsion, have also been shown to be a contributing factor to higher values of foot loading under the lateral forefoot (De Cock et al. 2006; Hayafune et al. 1999). Finally, a decrease in the plantar foot loading characteristics at the 1st metatarsal and hallux again supports the view that overweight and obesity affects the biomechanical function of the paediatric foot and reinforces the need for intervention to encourage a more medial loading pattern at the forefoot in the feet of overweight and obese children.

Emerging from this analysis is support of the view that children who are overweight and obese could be at risk of developing foot discomfort as a consequence of the elevated and prolonged pressures and forces acting upon the immature musculoskeletal structure of the paediatric foot and that overweight and obese children display similar patterns of plantar foot loading and as such earlier intervention is required. This work also provides early evidence for the use of cluster analysis in identifying groups of participants with similar foot loading characteristics in order to establish evidence based intervention strategies with the aim to reduce high regional plantar pressures and forces that could then be used as a foundation to inform clinical care. Due to similarities in their foot loading patterns, overweight and obese children could be prescribed the same group-specific intervention with the expectation that it would reduce corresponding elevated foot loading. As a result further longitudinal work is required to determine whether overweight and obese children would benefit from appropriate therapeutic footwear that provides adequate cushioning during common daily activities and/or from foot orthoses that encourages a more medial loading pattern at the forefoot.

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5.5 Chapter Summary

Following analysis of the plantar foot loading characteristics of children during barefoot level walking it has been identified that differences exist between obese, overweight and normal weight children. Comparative analysis indicated that:

- Overweight children generated significantly greater peak and temporal characteristics of foot loading at the MID and 2-5MTPJ regions in comparison to normal weight children.
- A similar trend was reported in the obese children with significant increases also found at the LH and MH in comparison to the normal weight children.
- When peak force was normalised to body mass a significant increase at the MID and 2-5MTPJ was still reported in the obese and overweight children.
- Normal weight children demonstrated increased peak and temporal loading characteristics at the 1MTPJ and HAL.

Foot type classification through cluster analysis adds further weight to these findings and indicated that:

- The majority of overweight and obese children loaded the plantar surface of their foot differently in comparison to normal weight children with two heterogeneous patterns of foot loading being identified.
- Obese (86.4%) and overweight (77.3%) children generated significantly greater peak and temporal characteristics of foot loading at the LH, MH, MID and 2-5MTPJ and normalised peak force values at the MID and 2-5MTPJ.
- Plantar foot loading at the 1MTPJ and HAL was greater for the majority of normal weight children (94.6%).

This work provides evidence as to the impact of overweight and obesity on the biomechanical function of the paediatric foot. In addition, evidence has emerged with regards to the impact of obesity on the temporal-spatial, kinematic and kinetic biomechanical function of the entire lower limb in children. The following chapter will look to determine the impact of overweight and obesity on the temporal-spatial and lower limb kinematic and kinetic gait characteristics of children, as well as investigate the relationship between plantar foot loading and the biomechanics of the lower limb.

CHAPTER SIX: COMPARISON OF TEMPORAL-SPATIAL AND LOWER LIMB KINEMATIC AND KINETIC GAIT PARAMETERS IN OBESE, OVERWEIGHT AND NORMAL WEIGHT CHILDREN

6.1 Introduction

Clinical gait analysis facilitates the assessment of walking biomechanics, which enables the identification of abnormal temporal-spatial, kinematic and kinetic movement patterns. It has been proposed that obesity is associated with altered lower limb biomechanics with several authors identifying differences in the temporal-spatial, kinematic and kinetic gait parameters of overweight and obese children relative to their normal weight peers (McMillan et al. 2009, 2010; Morrison et al. 2008; Shultz et al. 2009) the results of which have been discussed in sections 2.3.3.5 (page 47), 2.3.3.6 (page 49) and 2.3.3.7 (page 53) respectively. However, existing research has neglected to consider the gait biomechanics in overweight children and as yet no study has determined whether children who are overweight display similar changes in the lower limb biomechanical movement characteristics compared to their obese counterparts. With the increased combined prevalence of overweight and obese children in the UK, this work is of importance as current trends in obesity management are centred on weight loss and increased activity with a shift towards earlier intervention emerging, with the aim of preventing co-morbidities before children are obese.

Furthermore, the majority of research has focussed on temporal-spatial and kinematic adaptations alone, often within a single plane of motion and across the entire gait cycle. As a result, a comprehensive three-dimensional approach to the data analysis on the biomechanics of the lower limb in overweight and obese children is lacking. Finally, no study has sought to investigate the relationship between plantar foot loading and its impact on the biomechanics of the lower limb in overweight and obese children. These results could be used as a foundation to inform clinical care, as plantar pressure assessment offers a cheaper alternative to three-dimensional gait analysis, in the first line of clinical assessment when evaluating lower limb function in children; thereby potentially increasing the access to clinical services for these children.

This chapter will describe the impact of overweight and obesity on the temporal-spatial and tri-planar kinematic and kinetic parameters of the hip, knee and ankle in children, aged 7 to 11 years, throughout the gait cycle. It was hypothesised that overweight and obese children would demonstrate altered temporal-spatial gait characteristics as well as altered lower limb kinematic and kinetic walking patterns during gait. It was also hypothesised that a relationship would be found between plantar foot loading and the joint kinematics and kinetics of the lower limb in overweight and obese children.

6.2 Methods

6.2.1 Participants

The method for the recruitment of schools and participants, including inclusion and exclusion criteria has been outlined in section 3.3 (page 61).

Forty-five participants were recruited to determine temporal-spatial and tri-planar kinematic and kinetic parameters of the hip, knee and ankle in children who were obese (N = 15), overweight (N = 15) and normal weight (N = 15) throughout the gait cycle. Participants were classified according to their BMI-SDS as outlined in section 3.4.1.6 (page 66). Participant characteristics are presented in Table 6.1 (page 123).

6.2.2 Experimental Procedures

Anthropometrical and temporal-spatial, kinematic and kinetic gait data was acquired according to the methods outlined in sections 3.4.1 (page 63) and 3.4.3 (page 71) respectively.

6.2.3 Data Analysis

A comparison of the anthropometric, temporal-spatial, kinematic and kinetic gait data was undertaken and performed according to the methods described in section 3.5.2 (page 81). Relationships between foot loading characteristics and the kinematic and kinetic biomechanics of the lower limb during walking were evaluated according to the methods described in section 3.5.4 (page 84).

Table 6.1. Anthropometric data (Mean ± SD) for the obese (N = 15), overweight (N = 15) and normal weight (N = 15) children

	Total (N=45)	**Obese Children**	**Overweight Children**	**Normal Weight Children**
Gender (M/F)	34/11	11/4	12/3	11/4
Age (years)	9.64 ± 1.66	9.73 ± 1.75	9.67 ± 1.64	9.60 ± 1.03
Body Mass (kg)	46.39 ± 18.21	61.63 ±20.89	42.46 ± 9.53ł	35.07 ± 10.07*†
Stature (m)	1.48 ± 0.16	1.48 ± 0.18	1.50 ± 0.14	1.47 ± 0.12
BMI (kg/m^2)	20.21 ± 4.35	24.87 ± 3.72	19.55 ± 1.35ł	16.21 ± 1.89*†
BMI-SDS	1.24 ± 1.36	2.57 ± 0.52	1.35 ± 0.49ł	-0.21 ± 1.16*†
Leg Length (cm)	84.56 ± 8.33	85.54 ± 11.92	86.94 ± 5.72	83.82 ± 9.52
Knee Width (cm)	9.07 ± 0.66	10.69 ± 1.36	9.75 ± 0.31	8.74 ± 0.74
Ankle Width (cm)	6.56 ± 0.54	6.91 ± 0.74	6.62 ± 0.33	6.24 ± 0.55

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

ł denotes a significant difference between obese and overweight children ($p<0.05$)

6.3 Results

6.3.1 Temporal-spatial Parameters during Walking

Descriptive data for the absolute and normalised temporal-spatial parameters in obese, overweight and normal weight participants is summarised in Table 6.2 (page 123). Significant group differences were reported for velocity ($F_{(2,43)} = 27.14$, $p<0.05$), cadence ($F_{(2,43)} = 10.63$, $p<0.05$), step length ($F_{(2,43)} = 17.56$, $p<0.05$) and time spent in double-support ($F_{(2,43)} = 14.54$, $p<0.05$) (Table 6.2, page 123). Post-hoc analysis revealed overweight and obese children walked with a significantly lower velocity

($p<0.05$), smaller step length ($p<0.05$) and spent significantly longer in double-support ($p<0.05$) in comparison to the normal weight group (Table 6.2, below). The obese participants also walked with a significantly lower cadence ($p<0.05$) when compared to the normal weight children (Table 6.2, below).

Analysis of the normalised temporal-spatial parameters revealed significant group differences in velocity ($F_{(2,43)} = 3.51$, $p<0.05$) and step length ($F_{(2,43)} = 2.01$, $p<0.05$) between overweight ($p<0.05$) and obese ($p<0.05$) children relative to the normal weight group, with these participants demonstrating a significant decrease in velocity and a significantly shorter step length (Table 6.2, below).

Table 6.2. Summary of the absolute and normalised temporal-spatial gait parameters for the obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

	Obese Children	**Overweight Children**	**Normal Weight Children**
Absolute temporal-spatial parameters			
Velocity (m/sec)	0.95 ± 0.35	1.05 ± 0.14	1.18 ± 0.10*†
Cadence (steps/min)	99.29 ± 21.90	102.61 ± 28.60	106.24 ± 15.79*
Step Length (m)	0.58 ± 0.07	0.60 ± 0.06	0.67 ± 0.05*†
Step Width (m)	0.12 ± 0.04	0.14 ± 0.02	0.14 ± 0.04
Single Support (sec)	0.42 ± 0.07	0.43 ± 0.04	0.47 ± 0.07
Double Support (sec)	0.25 ± 0.05	0.24 ± 0.06	0.15 ± 0.05*†
Normalised temporal-spatial parameters			
Velocity (m/sec)^1	0.26 ± 0.07	0.27 ± 0.05	0.33 ± 0.06*†
Cadence (steps/min)^1	22.77 ± 5.04	23.83 ± 5.19	24.87 ± 5.15
Step Length (m)^2	0.68 ± 0.08	0.70 ± 0.04	0.80 ± 0.03*†
Step Width (m)^2	0.14 ± 0.06	0.16 ± 0.02	0.17 ± 0.02
Single Support (sec)^3	0.10 ± 0.00	0.10 ± 0.00	0.11 ± 0.01
Double Support (sec)^3	0.06 ± 0.00	0.06 ± 0.00	0.04 ± 0.00

^{1}Normalised to (9.81/leg length)^{½}; ^{2}Normalised to leg length; ^{3}Normalised to (9.81 x leg length)^{½} (Hof, 1996)

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

6.3.2 Kinematic Parameters during Walking

6.3.2.1 Sagittal Plane Joint Angles

Mean sagittal plane joint movements for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.1 (page 126) and maximum and minimum angles during the phases of initial double-support (IDS), single-support (SS), terminal double-support (TDS) and swing (SW) are reported in Table 6.3 (page 125). Positive values indicate flexion and negative values extension.

6.3.2.1.1 Hip

The movement curve is similar for all groups, except that the obese participants demonstrated increased hip flexion throughout the gait cycle (Figure 6.1, page 126). Significant group differences were reported for minimum hip angle during SS ($F_{(2,43)} = 10.097$, $p<0.05$), TDS ($F_{(2,43)} = 9.426$, $p<0.05$) and SW ($F_{(2,43)} = 3.596$, $p<0.05$) and maximum hip angle during TDS ($F_{(2,43)} = 6.955$, $p<0.05$) (Table 6.3, page 125). Post-hoc testing revealed obese children demonstrated significantly less hip extension during SS and TDS and significantly greater hip flexion in TDS and at the start of SW in comparison to normal weight participants ($p<0.05$) (Table 6.3, page 125).

6.3.2.1.2 Knee

The double flexion angular pattern of movement is similar for all groups (Figure 6.1, page 126). No significant group differences were reported throughout the gait cycle (Table 6.3, page 125).

6.3.2.1.3 Ankle

The quadruple pattern of motion is similar for all groups, except the normal weight participants demonstrate greater plantarflexion towards the end of TDS, when compared to the overweight and obese children (Figure 6.1, page 126). Significant group differences were reported for minimum ankle angle during TDS ($F_{(2,43)} = 6.385$, p<0.05) and SW ($F_{(2,43)}$ = 3.712, p<0.05) and maximum ankle angle during SW ($F_{(2,43)}$ = 4.526, p<0.05) (Table 6.3, below). Post-hoc analysis revealed that overweight (p<0.05) and obese (p<0.05) children demonstrated significantly less ankle plantarflexion during TDS and at the start of SW and significantly greater ankle dorsiflexion during mid-swing in comparison to the normal weight children (Table 6.3, below).

Table 6.3. Summary of the maximum and minimum hip, knee and ankle sagittal plane joint angles during IDS, SS, TDS and SW for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	**Overweight Children**	**Normal Weight Children**
Maximum and minimum joint angle (^{0})				
IDS	Hip Max	33.56 ± 12.86	32.63 ± 5.03	32.72 ± 5.33
	Hip Min	28.62 ± 13.60	28.62 ± 4.97	28.72 ± 5.65
	Knee Max	12.39 ± 7.47	12.86 ± 6.72	13.74 ± 7.12
	Knee Min	0.93 ± 4.30	1.58 ± 4.48	2.38 ± 4.04
	Ankle Max	-2.98 ± 4.08	-2.51 ± 3.33	-2.07 ± 3.54
	Ankle Min	-8.98 ± 3.37	-8.00 ± 3.68	-9.17 ± 6.04
SS	Hip Max	29.83 ± 9.60	27.74 ± 5.12	28.06 ± 5.77
	Hip Min	-1.27 ± 4.33	-4.25 ± 4.51	-9.48 ± 5.29*
	Knee Max	13.12 ± 6.92	14.03 ± 6.43	15.03 ± 7.92
	Knee Min	1.30 ± 3.65	1.29 ± 4.71	2.59 ± 5.26
	Ankle Max	11.74 ± 4.17	11.42 ± 4.79	10.31 ± 3.43
	Ankle Min	-5.17 ± 3.45	-3.84 ± 7.69	-1.95 ± 3.14
TDS	Hip Max	3.93 ± 6.48	-1.28 ± 4.36	-4.83 ± 7.39*
	Hip Min	-2.03 ± 4.39	-5.12 ± 4.54	-10.41 ± 5.82*
	Knee Max	28.96 ± 9.53	29.27 ± 4.40	29.47 ± 11.34
	Knee Min	8.28 ± 5.91	8.94 ± 4.33	10.13 ± 6.49
	Ankle Max	10.25 ± 3.28	10.67 ± 4.92	6.84 ± 4.69
	Ankle Min	-7.93 ± 7.19	-8.71 ± 6.72	-16.89 ± 6.63*†
SW	Hip Max	34.87 ± 11.12	32.27 ± 4.48	33.87 ± 4.81
	Hip Min	3.39 ± 7.25	-1.29 ± 4.47	-3.47 ± 7.79*
	Knee Max	52.98 ± 8.46	55.83 ± 3.84	54.01 ± 11.15
	Knee Min	-1.31 ± 4.45	-1.88 ± 5.26	-1.21 ± 4.36
	Ankle Max	3.12 ± 11.03	2.59 ± 4.11	0.22 ± 2.82*†
	Ankle Min	-16.04 ± 4.96	-15.59 ± 7.79	-22.59 ± 8.02*†

* denotes a significant difference between obese and normal weight children (p<0.05)

† denotes a significant difference between overweight and normal weight children (p<0.05)

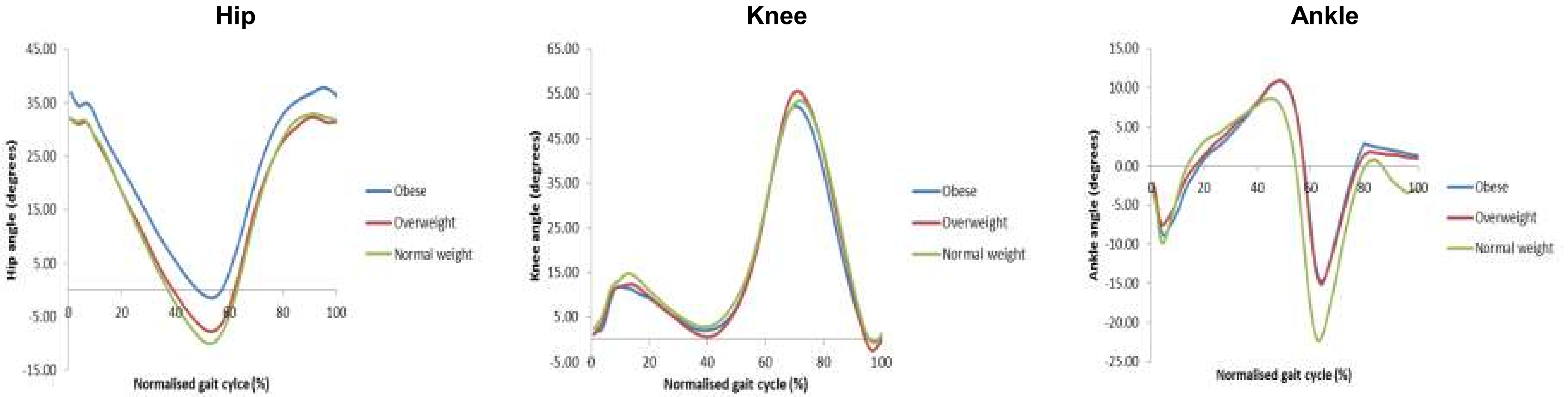


Figure 6.1. Group mean *sagittal plane joint angles* of the hip, knee and ankle in obese, overweight and normal weight children

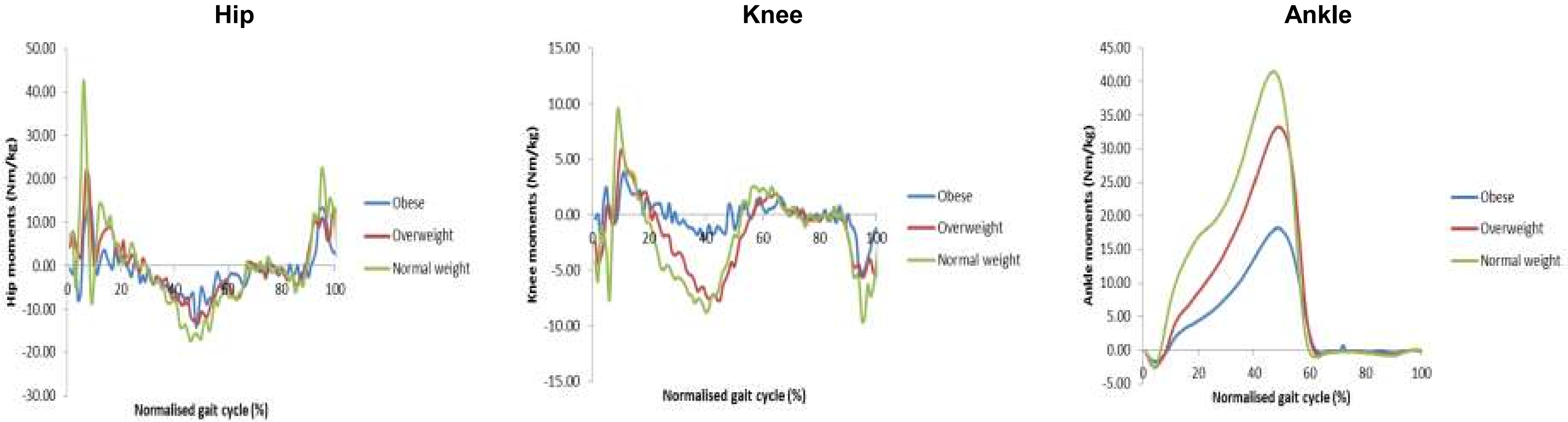


Figure 6.2. Group mean *sagittal plane external joint moments* of the hip, knee and ankle in obese, overweight and normal weight children

6.3.2.2 Frontal Plane Joint Angles

Mean frontal plane joint movements for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.3 (page 129) and maximum and minimum angles during the phases of IDS, SS, TDS and SW are reported in Table 6.4 (page 128). Positive values indicate adduction and negative values abduction. No significant kinematic group differences were reported at the hip, knee and ankle in the frontal plane (Table 6.4, page 128).

6.3.2.2.1 Hip

The triple movement curve shows a similar pattern of motion for all groups, except that the hip of the obese participants is more adducted during SS when compared to the overweight and normal weight groups (Figure 6.3, page 129).

6.3.2.2.2 Knee

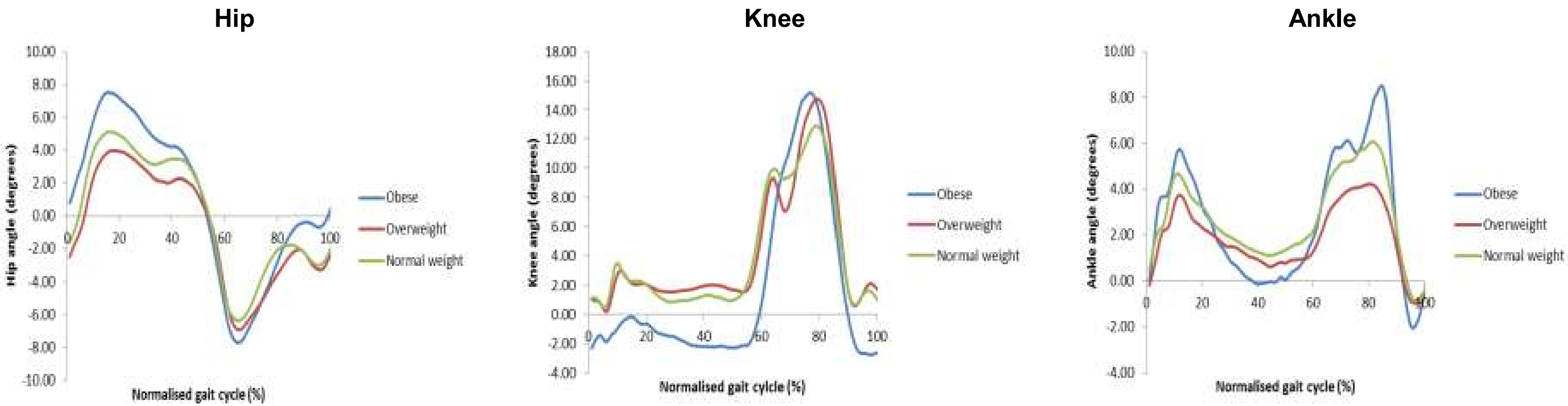
The movement curve is similar for all groups, except it appears to maintain an abducted position throughout stance in the obese participants in contrast to an adducted position in the overweight and normal weight children (Figure 6.3, page 129).

6.3.2.2.3 Ankle

The double adduction pattern of angular joint motion appears similar for all groups, except the obese participants appear to display greater adduction peaks during SS and SW in comparison to overweight and normal weight children (Figure 6.3, page 129).

Table 6.4. Summary of the maximum and minimum hip, knee and ankle *frontal plane joint angles* during IDS, SS, TDS and SW for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

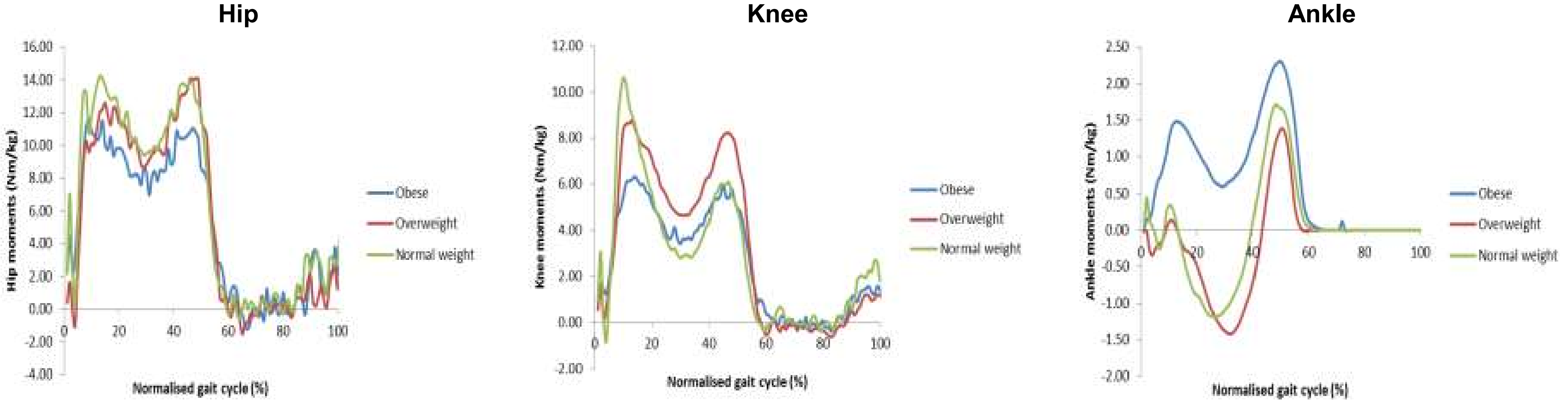
		Obese Children	**Overweight Children**	**Normal Weight Children**
Maximum and minimum joint angle (^{0})				
IDS	Hip Max	5.45 ± 4.54	2.66 ± 3.69	3.89 ± 3.61
	Hip Min	0.69 ± 4.27	-2.74 ± 3.91	-1.65 ± 3.40
	Knee Max	1.14 ± 4.98	2.81 ± 4.83	3.08 ± 3.75
	Knee Min	-4.13 ± 5.45	-1.46 ± 5.24	-1.13 ± 3.93
	Ankle Max	2.92 ± 2.06	3.46 ± 2.25	4.56 ± 3.96
	Ankle Min	-0.14 ± 3.07	-0.49 ± 2.32	0.05 ± 2.70
SS	Hip Max	7.43 ± 4.35	4.69 ± 3.43	5.78 ± 2.97
	Hip Min	1.25 ± 3.23	0.98 ± 3.12	1.40 ± 2.85
	Knee Max	1.85 ± 5.86	3.67 ± 4.37	3.16 ± 4.16
	Knee Min	-4.06 ± 5.52	-0.55 ± 4.08	-1.22 ± 4.24
	Ankle Max	3.28 ± 2.12	3.79 ± 2.66	4.79 ± 4.36
	Ankle Min	-0.30 ± 2.77	-0.09 ± 2.71	0.59 ± 2.55
TDS	Hip Max	1.39 ± 3.39	0.90 ± 3.27	1.59 ± 2.58
	Hip Min	-5.00 ± 4.54	-4.99 ± 2.62	-4.70 ± 3.49
	Knee Max	4.18 ± 11.61	6.03 ± 7.51	6.43 ± 9.40
	Knee Min	-4.49 ± 8.44	-0.42 ± 4.97	-0.66 ± 6.13
	Ankle Max	0.85 ± 1.94	1.12 ± 2.72	2.33 ± 2.79
	Ankle Min	-0.58 ± 1.97	0.07 ± 2.74	1.03 ± 2.56
SW	Hip Max	1.21 ± 3.59	-1.61 ± 2.56	-0.77 ± 3.03
	Hip Min	-8.53 ± 3.33	-7.78 ± 2.44	-6.72 ± 3.12
	Knee Max	18.94 ± 15.13	16.79 ± 9.05	14.81 ± 11.75
	Knee Min	-6.14 ± 7.91	-2.77 ± 7.19	-5.27 ± 9.57
	Ankle Max	7.11 ± 1.85	4.64 ± 1.98	6.49 ± 5.07
	Ankle Min	-2.36 ± 2.04	-1.68 ± 2.53	-1.47 ± 2.38


Hip

Knee

Ankle

Figure 6.3. Group mean *frontal plane joint angles* of the hip, knee and ankle in obese, overweight and normal weight children


Hip

Knee

Ankle

Figure 6.4. Group mean *frontal plane external joint moments* of the hip, knee and ankle in obese, overweight and normal weight children

6.3.2.3 Transverse Plane Joint Angles

Mean transverse plane joint movements for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.5 (page 132) and maximum and minimum angles during the phases of IDS, SS, TDS and SW are reported in Table 6.5 (page 131). Positive values indicate internal rotation and negative values external rotation. No significant kinematic group differences were reported at the hip, knee and ankle in the transverse plane (Table 6.5, page 131).

6.3.2.3.1 Hip

The movement curve is similar for all groups, except the hip appears to be more externally rotated throughout stance in the obese participants when compared to the overweight and normal weight children (Figure 6.5, page 132).

6.3.2.3.2 Knee

The quadruple pattern of angular motion is similar for all groups (Figure 6.5, page 132).

6.3.2.3.3 Ankle

The quadruple pattern of angular motion is similar for all groups, except the obese participants internally rotate during SS and TDS in contrast to the overweight and normal weight children who maintain external rotation throughout stance (Figure 6.5, page 132).

Table 6.5. Summary of the maximum and minimum hip, knee and ankle *transverse plane joint angles* during IDS, SS, TDS and SW for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	**Overweight Children**	**Normal Weight Children**
Maximum and minimum joint angle $(^0)$				
IDS	Hip Max	1.20 ± 15.78	5.03 ± 11.20	8.73 ± 21.08
	Hip Min	-18.05 ± 21.68	-11.19 ± 15.45	-9.71 ± 21.49
	Knee Max	9.75 ± 15.01	4.33 ± 15.59	9.24 ± 11.98
	Knee Min	-13.29 ± 12.31	-11.92 ± 15.59	-7.67 ± 8.39
	Ankle Max	4.13 ± 18.99	4.23 ± 11.18	0.14 ± 20.18
	Ankle Min	-22.06 ± 18.28	-18.06 ± 10.19	-25.57 ± 19.15
SS	Hip Max	1.39 ± 17.26	6.10 ± 12.79	9.92 ± 20.73
	Hip Min	-13.76 ± 21.06	-3.93 ± 12.50	-4.00 ± 18.28
	Knee Max	8.66 ± 13.06	4.38 ± 13.95	10.29 ± 13.16
	Knee Min	-7.17 ± 14.79	-7.49 ± 16.36	-2.63 ± 12.97
	Ankle Max	5.42 ± 19.17	2.37 ± 13.99	-4.37 ± 17.86
	Ankle Min	-23.94 ± 18.62	-19.19 ± 11.28	-26.32 ± 19.51
TDS	Hip Max	-3.16 ± 18.89	5.76 ± 14.54	9.57 ± 21.55
	Hip Min	-8.25 ± 18.83	-0.37 ± 13.65	1.82 ± 20.11
	Knee Max	5.76 ± 13.92	2.45 ± 13.91	6.43 ± 14.07
	Knee Min	-2.59 ± 15.39	-3.61 ± 14.37	-0.11 ± 12.99
	Ankle Max	3.54 ± 20.00	1.07 ± 14.52	-6.94 ± 18.10
	Ankle Min	-6.90 ± 19.33	-4.45 ± 14.65	-14.86 ± 18.69
SW	Hip Max	12.44 ± 17.56	15.99 ± 12.24	18.63 ± 23.24
	Hip Min	-24.35 ± 17.53	-17.52 ± 16.38	-20.79 ± 15.93
	Knee Max	19.36 ± 14.03	15.26 ± 10.76	19.24 ± 12.22
	Knee Min	-15.53 ± 11.92	-13.14 ± 14.63	-10.04 ± 8.86
	Ankle Max	17.37 ± 13.99	11.69 ± 13.52	10.24 ± 15.06
	Ankle Min	-29.33 ± 17.29	-23.63 ± 8.57	-33.24 ± 18.05

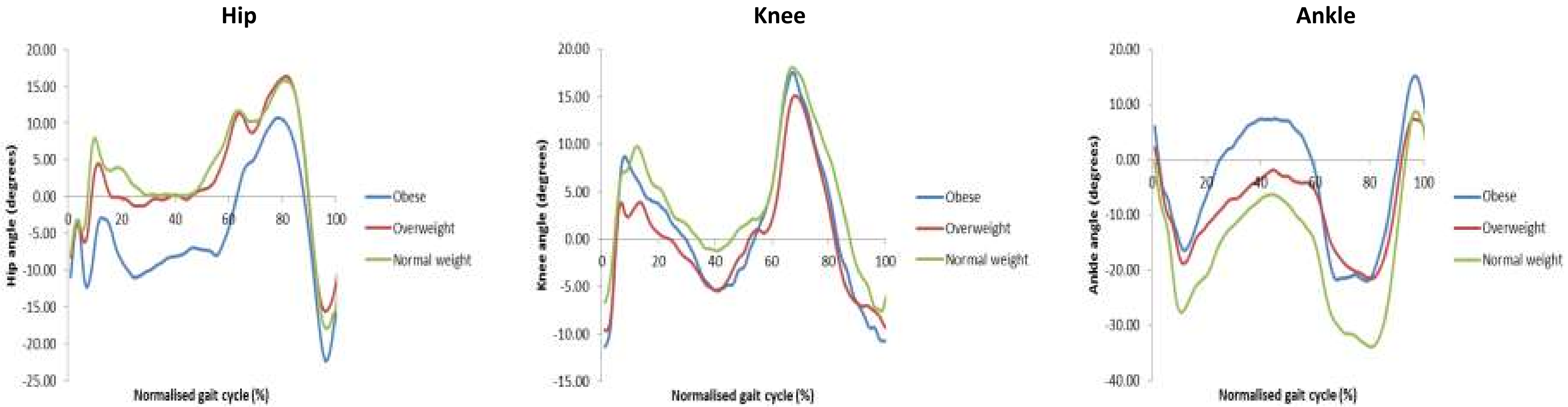


Figure 6.5. Group mean *transverse plane joint angles* of the hip, knee and ankle in obese, overweight and normal weight children

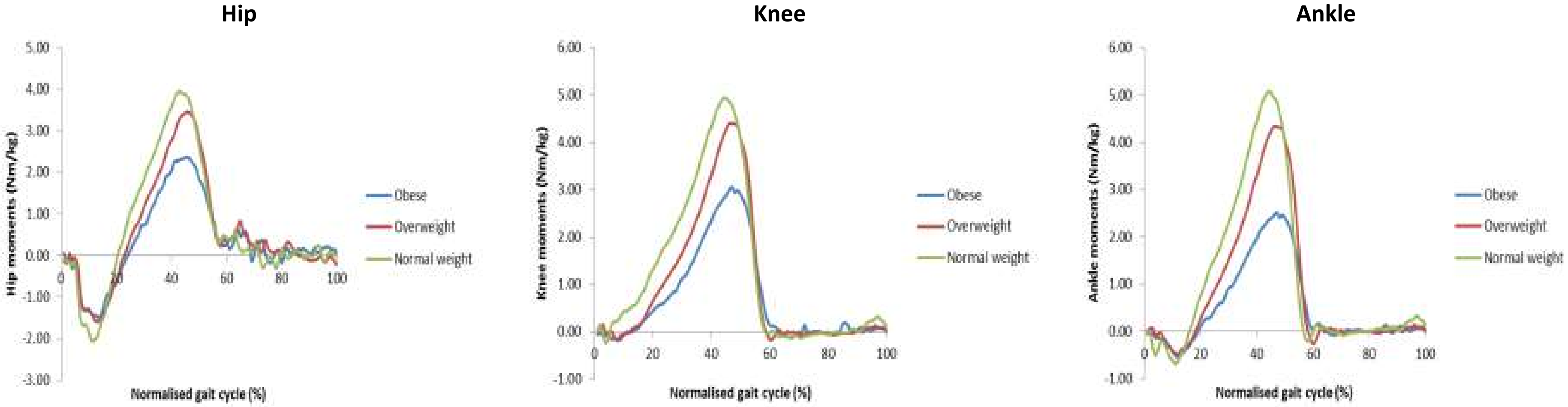


Figure 6.6. Group mean *transverse plane external joint moments* of the hip, knee and ankle in obese, overweight and normal weight children

6.3.3 Kinetic Parameters during Walking

6.3.3.1 Vertical Ground Reaction Forces

Mean vertical ground reaction forces for obese, overweight and normal weight children are plotted against % of total gait cycle in Figure 6.7 (below) and maximum values during the phases of IDS, SS and TDS are reported in Table 6.6 (below). Significant group differences were reported for maximum vertical ground reaction forces during IDS ($F_{(2,43)} = 3.220$, $p<0.05$) when comparing obese and normal weight children ($p<0.05$) with values higher for the obese participants (Table 6.6, below).

Table 6.6. Summary of the maximum *vertical ground reaction forces* during IDS, SS and TDS for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	Overweight Children	Normal Weight Children
Vertical Ground Reaction Force (N)				
IDS	Max	581.43 ± 149.76	483.10 ± 143.34	437.82 ± 65.28*
SS	Max	639.82 ± 50.77	554.82 ± 59.92	535.30 ± 105.05
TDS	Max	593.62 ± 80.34	539.52 ± 39.52	526.37 ± 36.62

* denotes a significant difference between obese and normal weight children (p<0.05)

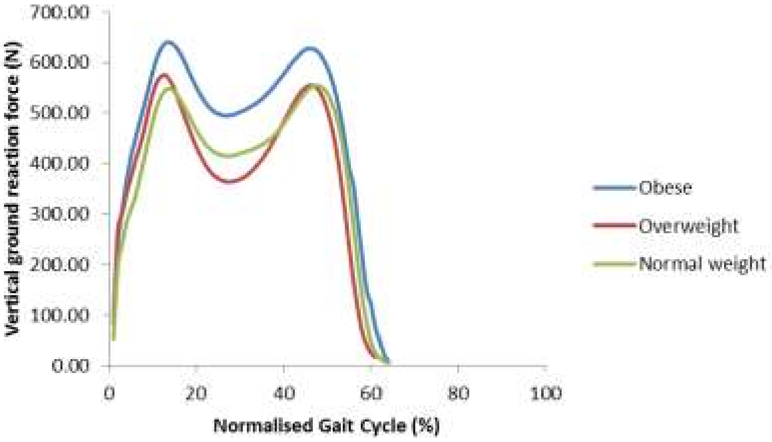


Figure 6.7. Group mean *vertical ground reaction forces* in obese, overweight and normal weight children during level walking

6.3.3.2 Sagittal Plane External Joint Moments

Mean sagittal plane external joint moments for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.2 (page 126) and maximum and minimum external joint moments during the phases of IDS, SS and TDS are reported in Table 6.7 (page 136). Positive values indicate flexor moments and negative values extensor moments.

6.3.3.2.1 Hip

The moment curves are similar for all groups (Figure 6.2, page 126). No significant group differences were reported for absolute external hip joint moments (Table 6.7, page 136). Analysis of the normalised data revealed significant group differences for minimum hip moments during TDS ($F_{(2,43)} = 5.362$, $p<0.05$) (Table 6.7, page 136). Post-hoc testing revealed a significant increase in the magnitude of the extensor moments in the normal weight children when compared to the obese ($p<0.05$) and overweight participants (Table 6.7, page 136).

6.3.3.2.2 Knee

The moment curves are similar for all groups (Figure 6.2, page 126). No significant group differences were reported for absolute or normalised external knee joint moments (Table 6.7, page 136).

6.3.3.2.3 Ankle

The moment curves show a similar pattern for all groups, except the normal weight and overweight participants demonstrate larger dorsiflexion moments throughout stance when compared to the obese children (Figure 6.2, page 126). Significant group differences were reported for absolute maximum ankle moments during IDS ($F_{(2,43)} = 8.063$, $p<0.05$) and SS ($F_{(2,43)} = 2.776$, $p<0.05$) and minimum ankle moments during SS ($F_{(2,43)} = 8.006$, $p<0.05$) and TDS ($F_{(2,43)} = 4.392$, $p<0.05$) (Table 6.7, page 136). Post-hoc testing revealed a significant increase in the magnitude of dorsiflexor and plantarflexor moments in the normal weight children when compared to the obese participants ($p<0.05$) (Table 6.7, page 136). Significant group differences were also reported between overweight and normal weight groups ($p<0.05$) for the maximum ankle moments during IDS and maximum and minimum ankle moments during SS. Again all values were greater in the normal weight group (Table 6.7, page 136).

Analysis of the normalised data revealed significant group differences for maximum ankle moments during IDS ($F_{(2,43)} = 6.874$, $p<0.05$), SS ($F_{(2,43)} = 17.856$, $p<0.05$) and TDS ($F_{(2,43)} = 11.369$, $p<0.05$) and minimum ankle moments during SS ($F_{(2,43)} = 6.781$, $p<0.05$) and TDS ($F_{(2,43)} = 5.362$, $p<0.05$) (Table 6.7, page 136). Post-hoc testing revealed a significant increase in magnitude of dorsiflexor and plantarflexor moments in the normal weight children when compared to the overweight ($p<0.05$) and obese ($p<0.05$) participants (Table 6.7, page 136).

Table 6.7. Summary of the maximum and minimum hip, knee and ankle *sagittal plane external joint moments* during IDS, SS and TDS for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	**Overweight Children**	**Normal Weight Children**
Absolute maximum and minimum moments (Nm)				
IDS	Hip Max	75.03 ± 29.28	47.98 ± 40.34	41.38 ± 12.98
	Hip Min	-31.11 ± 23.79	-5.94 ± 3.49	-11.22 ± 10.52
	Knee Max	76.25 ± 51.24	33.12 ± 14.01	32.26 ± 14.72
	Knee Min	-21.35 ± 6.10	-20.38 ± 6.37	-20.69 ± 6.31
	Ankle Max	18.91 ± 11.59	25.48 ± 10.62	32.97 ± 11.22*†
	Ankle Min	-3.05 ± 2.57	-7.64 ± 6.52	-7.72 ± 3.86
SS	Hip Max	35.77 ± 21.83	24.60 ± 6.15	30.96 ± 18.09
	Hip Min	-41.23 ± 24.86	-9.43 ± 4.03	-24.84 ± 19.44
	Knee Max	55.17 ± 33.95	27.06 ± 8.61	30.60 ± 6.84
	Knee Min	-40.62 ± 24.86	-18.04 ± 7.38	-27.01 ± 9.36
	Ankle Max	87.31 ± 55.78	62.32 ± 35.67	101.52 ± 39.25*†
	Ankle Min	13.94 ± 9.70	13.04 ± 8.61	33.84 ± 6.84*†
TDS	Hip Max	-15.50 ± 27.90	-2.15 ± 1.16	-4.68 ± 4.82
	Hip Min	-38.44 ± 7.44	-19.78 ± 6.02	-30.42 ± 15.21
	Knee Max	27.28 ± 18.60	5.59 ± 1.72	22.23 ± 10.53
	Knee Min	-4.34 ± 9.30	-5.52 ± 2.25	-7.02 ± 3.51
	Ankle Max	63.86 ± 16.74	50.74 ± 16.34	75.27 ± 17.55
	Ankle Min	4.96 ± 6.20	2.15 ± 1.87	-1.56 ± 6.84*
Normalised maximum and minimum moments (Nm/kg)				
IDS	Hip Max	1.23 ± 0.48	1.13 ± 0.95	1.18 ± 0.37
	Hip Min	-0.51 ± 0.39	-0.14 ± 0.20	-0.32 ± 0.30
	Knee Max	1.25 ± 0.84	0.78 ± 0.33	0.92 ± 0.79
	Knee Min	-0.35 ± 0.10	-0.48 ± 0.15	-0.59 ± 0.18
	Ankle Max	0.31 ± 0.19	0.60 ± 0.25	0.94 ± 0.32*†
	Ankle Min	-0.05 ± 0.07	-0.18 ± 0.08	-0.22 ± 0.11
SS	Hip Max	0.59 ± 0.36	0.60 ± 0.15	0.86 ± 0.53
	Hip Min	-0.68 ± 0.41	-0.23 ± 0.83	-0.69 ± 0.54
	Knee Max	0.91 ± 0.56	0.66 ± 0.21	0.85 ± 0.19
	Knee Min	-0.67 ± 0.41	-0.44 ± 0.18	-0.75 ± 0.26
	Ankle Max	1.44 ± 0.92	1.52 ± 0.87	2.82 ± 1.09*†
	Ankle Min	0.23 ± 0.16	0.34 ± 0.21	0.94 ± 0.19*†
TDS	Hip Max	-0.25 ± 0.45	-0.05 ± 0.12	-0.12 ± 0.38
	Hip Min	-0.62 ± 0.12	-0.46 ± 0.14	-0.78 ± 0.39*†
	Knee Max	0.44 ± 0.30	0.13 ± 0.04	0.57 ± 0.27
	Knee Min	-0.07 ± 0.15	-0.16 ± 0.64	-0.18 ± 0.09
	Ankle Max	1.03 ± 0.27	1.18 ± 0.38	1.93 ± 0.45*†
	Ankle Min	0.08 ± 0.10	0.05 ± 0.09	-0.04 ± 0.21*†

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

6.3.3.3 Frontal Plane External Joint Moments

Mean frontal plane external joint moments for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.4 (page 129) and maximum and minimum external joint moments during the phases of IDS, SS and TDS are reported in Table 6.8 (page 139). Positive values indicate adductor moments and negative values abductor moments.

6.3.3.3.1 Hip

The moment curves display a similar double pattern of adduction moments for all groups (Figure 6.4, page 129). Significant group differences were reported for absolute maximum hip moments during IDS ($F_{(2,43)} = 6.354$, $p<0.05$) and SS ($F_{(2,43)} = 7.846$, $p<0.05$) with a significant increase in the adductor moments reported in the obese children when compared to the normal weight participants ($p<0.05$) (Table 6.8, page 139). Significant group differences were also reported for absolute maximum hip moments during TDS ($F_{(2,43)} = 3.047$, $p<0.05$) when comparing obese and overweight children to those normal weight, with significantly increased adductor moments reported in the obese and overweight cohort. Analysis of the normalised data revealed a significant difference for maximum hip moments during SS ($F_{(2,43)} = 12.082$, $p<0.05$) between obese and normal weight children ($p<0.05$). In this instance normal weight children demonstrated increased adductor moments (Table 6.8, page 139).

6.3.3.3.2 Knee

The moment curves show a similar double pattern of adductor moments for all groups, except the first peak adductor moments for the normal weight children appears larger when compared to the overweight and obese groups (Figure 6.4, page 129). No significant group differences were reported for absolute external joint moments of the knee (Table 6.8, page 139). Analysis of the normalised data identified significant group differences for maximum knee moments during SS ($F_{(2,43)} = 10.042$, $p<0.05$) and minimum knee moments during TDS ($F_{(2,43)} = 7.806$, $p<0.05$) when comparing obese to normal weight children ($p<0.05$), with a significant increase in adductor and abductor moments reported in the normal weight group (Table 6.8, page 139).

6.3.3.3.3 Ankle

The moment curves demonstrate an altered pattern across the three groups. Adductor moments are maintained throughout stance in the obese children in contrast to the overweight and normal weight groups where abduction moments occur during SS (Figure 6.4, page 129). Significant group differences for absolute minimum ankle moments during SS ($F_{(2,43)} = 2.871$, $p<0.05$) were reported between obese and normal weight children ($p<0.05$), with the normal weight group reporting significantly greater abductor moments in contrast to the adductor moments in the obese participants (Table 6.8, page 139). Differences in the frontal plane external moments of the ankle were eliminated once normalised to body mass.

Table 6.8. Summary of the maximum and minimum hip, knee and ankle *frontal plane external joint moments* during IDS, SS and TDS for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	**Overweight Children**	**Normal Weight Children**
Absolute maximum and minimum moments (Nm)				
IDS	Hip Max	25.62 ± 14.03	15.71 ± 8.07	14.03 ± 7.01*
	Hip Min	-4.88 ± 3.05	-6.79 ± 5.94	-9.12 ± 2.81
	Knee Max	33.55 ± 27.45	25.48 ± 19.53	32.26 ± 8.77
	Knee Min	-7.93 ± 2.44	-19.98 ± 7.17	-29.81 ± 24.55
	Ankle Max	16.47 ± 10.98	14.86 ± 5.94	15.43 ± 9.64
	Ankle Min	-1.22 ± 5.49	-0.85 ± 3.40	-2.10 ± 0.70
SS	Hip Max	24.48 ± 19.52	18.04 ± 16.40	14.55 ± 3.64*
	Hip Min	6.06 ± 1.21	2.46 ± 5.74	7.56 ± 4.32
	Knee Max	12.73 ± 9.09	13.12 ± 8.20	16.20 ± 7.92
	Knee Min	-0.61 ± 2.73	-2.05 ± 3.28	-1.08 ± 1.80
	Ankle Max	12.73 ± 3.94	5.33 ± 9.93	11.52 ± 5.04
	Ankle Min	3.64 ± 1.21	-0.41 ± 1.64	-3.96 ± 1.08*
TDS	Hip Max	25.42 ± 15.96	22.79 ± 9.46	13.26 ± 4.29*†
	Hip Min	-2.48 ± 7.36	-4.73 ± 3.33	-12.87 ± 8.33
	Knee Max	19.22 ± 10.54	13.44 ± 2.21	15.21 ± 26.13
	Knee Min	-10.62 ± 0.96	-11.18 ± 4.73	-12.87 ± 20.67
	Ankle Max	13.64 ± 12.24	6.02 ± 6.98	12.48 ± 8.97
	Ankle Min	4.96 ± 0.62	-0.86 ± 3.87	0.78 ± 2.34
Normalised maximum and minimum moments (Nm/kg)				
IDS	Hip Max	0.42 ± 0.23	0.37 ± 0.19	0.40 ± 0.20
	Hip Min	-0.08 ± 0.05	-0.16 ± 0.14	-0.26 ± 0.08
	Knee Max	0.55 ± 0.45	0.60 ± 0.46	0.92 ± 0.25
	Knee Min	-0.13 ± 0.04	-0.40 ± 0.64	-0.85 ± 0.70
	Ankle Max	0.27 ± 0.18	0.35 ± 0.14	0.44 ± 0.56
	Ankle Min	-0.02 ± 0.09	-0.02 ± 0.08	-0.06 ± 0.02
SS	Hip Max	0.24 ± 0.06	0.44 ± 0.40	0.68 ± 0.82*
	Hip Min	0.10 ± 0.02	0.06 ± 0.14	0.21 ± 0.12
	Knee Max	0.21 ± 0.15	0.32 ± 0.20	0.45 ± 0.22*
	Knee Min	-0.01 ± 0.11	-0.05 ± 0.08	-0.03 ± 0.05
	Ankle Max	0.21 ± 0.23	0.13 ± 0.23	0.32 ± 0.14
	Ankle Min	0.06 ± 0.02	-0.01 ± 0.04	-0.11 ± 0.03
TDS	Hip Max	0.41 ± 0.38	0.53 ± 0.22	0.34 ± 0.11
	Hip Min	-0.04 ± 0.08	-0.11 ± 0.31	-0.13 ± 0.47
	Knee Max	0.31 ± 0.17	0.18 ± 0.17	0.39 ± 0.67
	Knee Min	-0.01 ± 0.08	-0.26 ± 0.11	-0.33 ± 0.53*
	Ankle Max	0.22 ± 0.12	0.14 ± 0.86	0.32 ± 0.23
	Ankle Min	0.08 ± 0.01	-0.02 ± 0.09	0.02 ± 0.06

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

6.3.3.4 Transverse Plane External Joint Moments

Mean transverse plane external joint moments for the obese, overweight and normal weight children at the hip, knee and ankle are plotted against % of total gait cycle in Figure 6.6 (page 132) and maximum and minimum external joint moments during the phases of IDS, SS and TDS are reported in Table 6.9 (page 142). Positive values indicate internal rotation moments and negative values external rotation moments.

6.3.3.4.1 Hip

The moment curves are similar for all groups, except the internal rotation moment peaks are larger in the overweight and normal weight children when compared to the obese participants (Figure 6.6, page 132). Significant group differences for absolute minimum hip moments during TDS ($F_{(2,43)} = 3.054$, $p<0.05$) were reported between obese and normal weight children ($p<0.05$), with the normal weight group reporting significantly greater external rotator moments (Table 6.9, page 142). Analysis of the normalised data identified significant group differences for minimum hip moments during IDS ($F_{(2,43)} = 6.327$, $p<0.05$) and maximum hip moments during SS ($F_{(2,43)} = 14.268$, $p<0.05$) and TDS ($F_{(2,43)} = 11.513$, $p<0.05$) (Table 6.9, page 142). Post-hoc testing revealed a significant increase in the magnitude of internal and external rotator moments in the normal weight children when compared to the obese participants ($p<0.05$) (Table 6.9, page 142). A significant increase in the magnitude of internal rotator moments during SS were also reported in the normal weight children when compared to the overweight participants ($p<0.05$) (Table 6.9, page 142).

6.3.3.4.2 Knee

The moment curves demonstrate a similar single internal rotation peak during stance for all groups; however the peak values appear greater in the overweight and normal weight children when compared to the obese participants (Figure 6.6, page 132). Significant group differences for absolute maximum knee moments during IDS ($F_{(2,43)} = 9.147$, $p<0.05$) and minimum knee moments during TDS ($F_{(2,43)} = 6.083$, $p<0.05$) were reported between obese and normal weight children, with the obese group reporting significantly greater internal and external rotator moments during these phases ($p<0.05$) (Table 6.9, page 142). Analysis of the normalised data revealed significant group differences for maximum knee moments during IDS ($F_{(2,43)} = 7.365$, $p<0.05$), SS ($F_{(2,43)} = 14.548$, $p<0.05$) and TDS ($F_{(2,43)} = 6.538$, $p<0.05$) and minimum knee moments during TDS ($F_{(2,43)} = 14.952$, $p<0.05$) (Table 6.9, page 142). Post-hoc testing revealed a significant increase in the magnitude of internal and external rotator moments in the normal weight children when compared to the obese participants ($p<0.05$) (Table 6.9, page 142). A significant increase in the magnitude of knee internal rotator moments during SS and TDS were also reported in the normal weight children when compared to the overweight group ($p<0.05$) (Table 6.9, page 142).

6.3.3.4.3 Ankle

The moment curves show a similar single internal rotation peak pattern for all groups, except peak values appear greater in the overweight and normal weight children when compared to the obese participants (Figure 6.6, page 132). Significant group differences for absolute maximum ankle moments during IDS ($F_{(2,43)} = 12.089$, $p<0.05$) were reported between obese and normal weight children ($p<0.05$), with the normal weight group reporting significantly greater internal rotator moments in contrast to external rotator moments in the obese participants (Table 6.9, page 142). Analysis of the normalised data revealed significant group differences for maximum ankle moments during IDS ($F_{(2,43)} = 9.842$, $p<0.05$), SS ($F_{(2,43)} = 11.366$, $p<0.05$) and TDS ($F_{(2,43)} = 14.119$, $p<0.05$) and minimum ankle moments during IDS ($F_{(2,43)} = 6.588$, $p<0.05$) and TDS ($F_{(2,43)} = 12.183$, $p<0.05$) (Table 6.9, page 142). Post-hoc analysis revealed a significant increase in the magnitude of internal and external rotator moments in the normal weight children when compared to the obese participants ($p<0.05$) (Table 6.9, page 142). A significant increase in the magnitude of internal rotator moments during IDS and SS were also reported in the normal weight children when compared to the overweight group ($p<0.05$) (Table 6.9, page 142).

Table 6.9. Summary of the maximum and minimum hip, knee and ankle <u>*transverse plane external joint moments*</u> during IDS, SS and TDS for obese (N = 15), overweight (N = 15) and normal weight (N = 15) children (Mean ± SD of three trials)

		Obese Children	**Overweight Children**	**Normal Weight Children**
Absolute maximum and minimum moments (Nm)				
IDS	Hip Max	4.27 ± 5.49	2.12 ± 4.01	2.81 ± 3.67
	Hip Min	-1.83 ± 7.58	-5.10 ± 1.23	-8.07 ± 4.56*
	Knee Max	-1.83 ± 5.99	4.67 ± 3.35	5.61 ± 1.04*
	Knee Min	-10.98 ± 6.71	-7.22 ± 4.86	-8.42 ± 8.94
	Ankle Max	-0.61 ± 1.24	2.55 ± 7.41	7.36 ± 7.18*
	Ankle Min	-20.13 ± 8.54	-17.41 ± 7.83	-21.39 ± 9.12
SS	Hip Max	6.67 ± 10.02	10.66 ± 7.79	17.36 ± 9.44
	Hip Min	-7.88 ± 3.65	-6.56 ± 9.93	-7.92 ± 3.04
	Knee Max	9.70 ± 7.29	7.79 ± 3.69	13.76 ± 8.28
	Knee Min	-0.61 ± 3.04	-0.82 ± 2.30	1.08 ± 0.54
	Ankle Max	12.73 ± 8.81	10.66 ± 7.79	17.36 ± 9.44
	Ankle Min	-0.61 ± 2.71	-0.82 ± 6.24	-4.32 ± 3.04
TDS	Hip Max	13.64 ± 10.30	11.61 ± 6.66	15.99 ± 4.43
	Hip Min	4.34 ± 4.72	2.15 ± 4.30	1.17 ± 2.62
	Knee Max	7.44 ± 3.38	6.45 ± 3.65	12.09 ± 7.83
	Knee Min	1.24 ± 4.34	-1.72 ± 1.88	-1.95 ± 3.15*
	Ankle Max	4.34 ± 1.16	6.88 ± 3.41	7.41 ± 5.74
	Ankle Min	-4.34 ± 5.42	-8.21 ± 9.03	-7.80 ± 2.34
Normalised maximum and minimum moments (Nm/kg)				
IDS	Hip Max	0.07 ± 0.09	0.05 ± 0.33	0.08 ± 0.96
	Hip Min	-0.03 ± 0.78	-0.12 ± 0.11	-0.23 ± 0.13*
	Knee Max	-0.03 ± 0.59	0.11 ± 0.55	0.16 ± 0.60*
	Knee Min	-0.18 ± 0.11	-0.17 ± 0.35	-0.24 ± 0.54
	Ankle Max	-0.01 ± 0.84	0.06 ± 0.41	0.21 ± 0.49*†
	Ankle Min	-0.33 ± 0.14	-0.41 ± 0.42	-0.61 ± 0.26*
SS	Hip Max	0.11 ± 0.66	0.26 ± 0.19	0.76 ± 0.54*†
	Hip Min	-0.13 ± 0.72	-0.16 ± 0.73	-0.22 ± 0.64
	Knee Max	0.16 ± 0.78	0.19 ± 0.09	0.66 ± 0.23*†
	Knee Min	-0.01 ± 0.38	-0.02 ± 0.30	0.03 ± 0.15
	Ankle Max	0.21 ± 0.97	0.26 ± 0.19	0.76 ± 0.54*†
	Ankle Min	-0.01 ± 0.49	-0.02 ± 0.64	-0.12 ± 0.64
TDS	Hip Max	0.22 ± 0.65	0.27 ± 0.62	0.41 ± 0.37*
	Hip Min	0.07 ± 0.56	0.05 ± 0.10	0.03 ± 0.58
	Knee Max	0.12 ± 0.49	0.15 ± 0.55	0.31 ± 0.97*†
	Knee Min	0.02 ± 0.07	-0.04 ± 0.16	-0.05 ± 0.85*
	Ankle Max	0.07 ± 0.18	0.16 ± 0.87	0.19 ± 0.66*
	Ankle Min	-0.07 ± 0.41	-0.16 ± 0.21	-0.20 ± 0.06*

* denotes a significant difference between obese and normal weight children ($p<0.05$)

† denotes a significant difference between overweight and normal weight children ($p<0.05$)

6.3.4 Relationships between Characteristics of Foot Loading and Kinematic and Kinetic Walking Parameters

Relationships between normalised peak force at the midfoot (MID) and 2nd-5th metatarsals (2-5MTPJ) and the significant ($p<0.05$) between-group kinematic and kinetic parameters were explored using Pearson's correlation coefficients on the obese and overweight children and with the data combined.

6.3.4.1 Relationship between Normalised Peak Force at the Midfoot and 2nd-5th Metatarsals and Kinematic Parameters during Walking

Relationships between normalised peak force at the MID and 2-5MTPJ and the significant ($p<0.05$) between-group kinematic parameters are reported in Table 6.10 (page 144). In all cases only sagittal plane kinematic data is presented as no significant group differences were reported for frontal and transverse plane data.

Loading at the MID was negatively correlated with minimum hip angle during SS (obese: $r = -0.41$, $p<0.05$; overweight: $r = -0.34$, $p<0.05$; combined: $r = -0.39$, $p<0.05$) and positively correlated with maximum ankle angle during SW (obese: $r = 0.65$, $p<0.01$; overweight: $r = 0.67$, $p<0.01$; combined: $r = 0.66$, $p<0.05$) in all three groups (Table 6.10, page 144). Loading at the 2-5MTPJ was negatively correlated with minimum hip (obese: $r = -0.38$, $p<0.05$; overweight: $r = -0.37$, $p<0.05$; combined: $r = -0.32$, $p<0.05$) and ankle angle during TDS (obese: $r = -0.60$, $p<0.01$; overweight: $r = -0.73$, $p<0.01$; combined: $r = -0.62$, $p<0.01$) in all three groups (Table 6.10, page 144).

6.3.4.2 Relationship between Normalised Peak Force at the Midfoot and 2nd-5th Metatarsals and Kinetic Parameters during Walking

Relationships between normalised peak force at the MID and 2-5MTPJ and the significant ($p<0.05$) between-group kinetic parameters are reported in Table 6.11 (page 145). In all cases only sagittal plane kinetic data is presented. Frontal and transverse plane data was excluded, as no significant relationships were found. Frontal and transverse plane data is reported in Appendix 7 (Tables A7.1, page 229 and A7.2, page 230).

No significant relationships were reported between normalised peak force at the MID and sagittal plane kinetic data. Loading at the 2-5MTPJ was negatively correlated with minimum hip moments during TDS (obese: r = -0.77, p<0.01; overweight: r = -0.85, p<0.01; combined: r = -0.61, p<0.01) and positively correlated with minimum ankle moments during TDS (obese: r = 0.59, p<0.05; overweight: r = 0.72, p<0.05; combined: r = 0.96, p<0.05) in all three groups (Table 6.11, page 145).

Table 6.10. Relationship between normalised peak force data at the MID and 2-5MTPJ and kinematic parameters during walking (r indicates the strength and the direction of a relationship between variables)

		Midfoot normalised peak force (r)	2^{nd}-5^{th} metatarsals normalised peak force (r)
Minimum hip angle during SS	Obese	-0.41*	-0.00
	Overweight	-0.34*	-0.25
	Combined	-0.39*	-0.12
Maximum hip angle during TDS	Obese	0.04	-0.02
	Overweight	0.41	-0.36
	Combined	0.11	-0.31
Minimum hip angle during TDS	Obese	-0.05	-0.38*
	Overweight	0.15	-0.37*
	Combined	-0.01	-0.32*
Minimum hip angle during SW	Obese	-0.05	0.09
	Overweight	0.03	-0.38
	Combined	-0.06	0.27
Minimum ankle angle during TDS	Obese	-0.28	-0.60**
	Overweight	-0.25	-0.73**
	Combined	-0.23	-0.62**
Maximum ankle angle during SW	Obese	0.65**	0.32
	Overweight	0.67**	0.26
	Combined	0.66*	0.30
Minimum ankle angle during SW	Obese	-0.08	0.41
	Overweight	0.11	0.47
	Combined	-0.03	0.40

*p<0.05; **p<0.01

Table 6.11. Relationship between normalised peak force data at the MID and 2-5MTPJ and kinetic parameter during walking (r indicates the strength and the direction of a relationship between variables)

		Midfoot normalised peak force (r)	2^{nd}-5^{th} metatarsals normalised peak force (r)
Maximum vertical ground reaction force during IDS	Obese	0.09	0.36
	Overweight	0.11	0.18
	Combined	0.13	0.20
Minimum hip moment during TDS	Obese	-0.17	-0.77**
	Overweight	0.17	-0.85**
	Combined	0.22	-0.61**
Maximum ankle moment during IDS	Obese	0.31	-0.08
	Overweight	-0.22	0.32
	Combined	0.27	-0.09
Maximum ankle moment during SS	Obese	0.23	0.39
	Overweight	-0.26	0.05
	Combined	0.06	-0.11
Maximum ankle moment during TDS	Obese	-0.24	-0.39
	Overweight	0.22	0.08
	Combined	0.29	-0.41
Minimum ankle moment during TDS	Obese	0.24	0.59*
	Overweight	0.07	0.72*
	Combined	0.37	0.96*

*p<0.05; **p<0.01

6.3.4.3 Characteristics of Foot Loading and Predictors of Kinematic and Kinetic Walking Parameters

Where significant correlations were identified between normalised peak force at the MID and 2-5MTPJ and lower limb kinematic and kinetic walking patterns in overweight and obese children, linear regression analysis was undertaken to establish whether these correlations form a basis for prediction. Variables were input into the regression model in a backward stepwise method as described in section 3.5.4 (page 84).

6.3.4.3.1. Midfoot Normalised Peak Force

Kinematic gait parameters that demonstrated a significant association with normalised peak force at the MID are presented in Table 6.12 (page 146). Loading at the MID significantly predicted maximum ankle angle during SW ($r^2 = 0.65$, $p<0.05$) (Table 6.12, below). The variance inflation factor (VIF) and tolerance statistic (TOL) were also within acceptable limits, out outlined in section 3.5.4 (page 84); as a result no variable was removed from the regression model.

Table 6.12. Linear regression models for MID normalised peak force predictors of minimum hip angle during SS and maximum ankle angle during SW in the obese and overweight groups combined (N = 30) (r^2 indicates what proportion of variance is accounted for by all the predictor variables in the regression model; F-ratio the strength of the proposed regression model; Standardised β-values refer to how many standard deviations a dependent variable will change, per standard deviation increase in the predictor variable; TOL the proportion of a variable's variance that is not accounted for by the other IVs in the model; VIF indicates how inflated the variance of the coefficient is, compared to what it would be if the variable were uncorrelated with any other variable in the model)

		r^2	F-ratio	Standardised β-values	TOL	VIF
Maximum ankle angle during swing						
Model 1	Midfoot normalised peak force	0.65*	7.144	0.46	0.416	2.404

*p<0.05

6.3.4.3.2 2nd-5th Metatarsal Normalised Peak Force

Kinematic and kinetic gait parameters that demonstrated a significant association with normalised peak force at the 2-5MTPJ are presented in Table 6.13 (page 147). Loading at the 2-5MTPJ significantly predicted minimum hip and ankle angle and minimum hip and ankle moments during TDS (Model 1: $r^2 = 0.69$, $p<0.05$) (Table 6.13, page 147). The VIF and TOL statistic were also within acceptable limits.

Table 6.13. Linear regression models for 2-5MTPJ normalised peak force predictors of minimum hip and ankle angle and minimum hip and ankle moments during TDS in the obese and overweight groups combined ($N = 30$) (r^2 indicates what proportion of variance is accounted for by all the predictor variables in the regression model; F-ratio the strength of the proposed regression model; Standardised β-values refer to how many standard deviations a dependent variable will change, per standard deviation increase in the predictor variable; TOL the proportion of a variable's variance that is not accounted for by the other IVs in the model; VIF indicates how inflated the variance of the coefficient is, compared to what it would be if the variable were uncorrelated with any other variable in the model)

		r^2	F-ratio	Standardised β-values	TOL	VIF
Minimum hip angle during terminal double support						
Minimum ankle angle during terminal double support						
Minimum hip moment during terminal double support						
Minimum ankle moment during terminal double support						
Model 1	2nd-5th Metatarsal normalised peak force	0.69*	4.417	0.64	0.560	4.240

*$p<0.05$

6.3.5 Summary of Key Results

6.3.5.1 Temporal-Spatial Parameters during Walking

- Compared to normal weight children, those who were overweight and obese demonstrated:
    - Significantly decreased walking velocity.
    - Significantly smaller step length.

6.3.5.2 Kinematic Parameters during Walking

- Compared to normal weight children, those who were overweight and obese demonstrated:
    - Significantly reduced ankle plantarflexion during TDS and SW.
    - Significantly increased ankle dorsiflexion during mid-swing.
    - Significantly reduced hip extension during SS, TDS and SW (obese only).

6.3.5.3 Kinetic Parameters during Walking

- Compared to normal weight children, those who were overweight and obese demonstrated:
    - Significantly greater vertical ground reaction forces during IDS (obese only).
    - Significantly reduced normalised hip extensor moments during TDS.
    - Significantly reduced normalised ankle dorsiflexor moments during IDS, SS and TDS and significantly reduced normalised ankle plantarflexor moments during TDS.
    - Significantly reduced normalised hip internal rotator moments during SS.
    - Significantly reduced normalised knee internal rotator moments during SS and TDS.
    - Significantly reduced normalised internal rotator moments at the ankle during IDS and SS.
    - Significantly reduced normalised hip and knee adduction moments during SS (obese only).
    - Significantly reduced normalised knee abductor moments during TDS (obese only).
    - Significantly reduced normalised hip external rotator moments during IDS and internal rotator moments during TDS (obese only).
    - Significantly reduced normalised knee internal rotator moments during IDS and external rotator moments during TDS (obese only).
    - Significantly reduced normalised ankle internal and external rotator moments during IDS and TDS (obese only).

6.3.5.4 Relationship between Characteristics of Foot Loading and Kinematic and Kinetic Walking Parameters

- Linear regression demonstrated:
    - Loading at the MID significantly predicted increased angles of ankle dorsiflexion during SW in overweight and obese children.

- Loading at the 2-5MTPJ significantly predicted lower hip extension and ankle plantarflexion angles and moments during TDS in overweight and obese children.

6.4 Discussion

This chapter aimed to determine the impact of overweight and obesity on the temporal-spatial and lower limb kinematic and kinetic gait characteristics of children aged 7 to 11 years; as well as investigate the relationship between plantar foot loading and the dynamic joint kinematic and kinetics of the lower limb in overweight and obese children.

6.4.1 Temporal-Spatial Parameters during Walking

It was hypothesised that overweight and obese children would demonstrate altered temporal-spatial gait characteristics when compared to that of normal weight children; with the data supporting this research hypothesis. Analysis of the absolute temporal-spatial parameters identified that overweight children walked with a significantly lower velocity, smaller step length and spent significantly longer time in double-support when compared with normal weight children. A similar trend was identified in the obese children, with a significant reduction in cadence also reported. When data was normalised to body size a significant reduction in velocity and step length remained in the overweight and obese children.

Altered temporal-spatial gait parameters of overweight and obese children in the present study are consistent with previous findings (Hills and Parker, 1991[a,b]; Morrison et al. 2008). These results suggest that overweight and obese children have a greater degree of instability during gait associated with their increased body mass, as has been previously reported (Deforche et al. 2009; Goulding et al. 2003; McGraw et al. 2000). Consequently, it may be appropriate to postulate that the significant reduction in velocity evident in the overweight and obese children is a compensatory measure to reduce instability during walking and also reduce tissue stress with a reduction in peak plantar pressures, as previously demonstrated in a group of young typically developing children (Rosenbaum et al. 2013). Furthermore, although speculative, the significant reduction in step length may be a compensatory measure to reduce lower limb joint moments and foot pressures, as has been previously reported in a group of young adults (Allet et al. 2001; Dreup et al. 2004).

The results from this phase of work suggest temporal-spatial changes in a child’s gait, may be associated with a smaller gain in body mass than first thought; indicated by a slower walking pattern in overweight and obese children. The specific causative factors associated with these changes cannot be confirmed from this work alone and may be as a result of differences reported in the kinematic and kinetic gait characteristics of overweight and obese children relative to those of normal weight; the impact of which will be discussed in sections 6.4.2 (page below) and 6.4.3 (page 156).

6.4.2 Kinematic Parameters during Walking

The second hypothesis was that overweight and obese children would demonstrate altered kinematic movement patterns at the hip, knee and ankle when compared to normal weight children. The results in the sagittal plane support the research hypothesis, identifying those children who were overweight and obese displayed marked differences in joint kinematics at the hip and ankle when compared to normal weight children.

Overweight children walked with significantly reduced angles of ankle plantarflexion late in TDS (-8.71^0) and early in SW (-15.59^0) and reported significantly greater angles of dorsiflexion during mid-swing (2.59^0) when compared to normal weight children (-16.89^0, -22.59^0 and 0.22^0 respectively) (Table 6.3, page 125). Similar trends were also reported when comparing obese (-7.93^0, -16.04^0 and 3.12^0 respectively) and normal weight children (Table 6.3, page 125). These results emphasise that kinematic changes at the ankle occur earlier than previously reported, with a smaller increase in body mass than first thought and suggests altered biomechanical function in overweight and obese children.

Plantarflexion of the ankle assists limb advancement and forward progression during walking (Levine et al. 2012). Reduced plantarflexion during TDS, evident in the overweight and obese children, may be indicative of a compromised ability to push-off and advance the lower limb during walking. These changes accompanied by reduced range of ankle joint motion in the overweight (-15.59-11.42^0) and obese children (-16.04-11.74^0) relative to those of normal weight (-22.59-10.31^0) highlight a change in function that may be as a result of the slower walking speeds reported in these children. Stansfield et al. (2001^{a,b}) reported that the speed of walking was an important factor in determining the lower limb gait patterns in children. Previous research has reported walking at slower speeds significantly reduced plantarflexion in a group of healthy children (van der Linden et al. 2002). Furthermore, Lai et al. (2008) demonstrated that a reduced range of ankle joint motion was accompanied with significantly slower walking speeds in a group of obese adults. This change in ankle function may also have contributed towards the reduced step length demonstrated in the overweight and obese children. This finding is supported with conclusions from Pease et al. (2005) who reported that reduced plantarflexion during late stance prevents a normal heel rise, which functionally shortens the stance limb, leading to a premature contralateral initial foot contact that decreases stride length.

Reduced joint range of motion has been demonstrated in obese adults and children (O’Malley et al. 2012; Park et al. 2010). Park et al. (2010) postulated that the excess subcutaneous adipose tissue deposited in the shank and ankle area of the obese would interpose and mechanically obstruct movements at the ankle. This is a possible mechanism to explain findings from the present study were reduced ankle joint motion was reported in the overweight and obese children. Previous research has demonstrated that a reduced range of plantarflexion during push-off may indicate tightness and/or weakness in the plantarflexor muscles (i.e. gastrocnemius and soleus). A recent study in children with obesity reported inverse associations between BMI and lower limb range of motion, including reduced ankle plantarflexion, as a result of reduced gastrocnemius flexibility (O'Malley et al. 2012). These results were re-affirmed in a cohort of obese young women who reported a reduced range of motion at the ankle, resulting from overexertion of the pre-tibial muscles and tightness in the gastrocnemius and soleus muscles simultaneously (da Silva-Tamu et al. 2013). However, the authors did not describe the methods used to assess muscular flexibility or tightness and as such these results should be interpreted with caution. Furthermore, evidence reports diminished lower extremity strength in obese children, although ankle plantarflexor strength was not assessed (O'Malley et al. 2012; Riddiford-Harland et al. 2006). Neither gastrocnemius flexibility nor plantarflexor strength were assessed in the present study and warrants further investigation to determine whether these parameters are associated with and predictors of change in ankle function.

Reduced plantarflexion during TDS may contribute towards the increased loading at the 2-5MTPJ, as attested by its significant relationship with normalised peak force at this site (Table 6.10, page 144). This supports previous research that demonstrated a change in ankle joint function alters plantar foot loading (Alentorn-Gali et al. 2013; Macklin et al. 2012; Sacco et al. 2009). Sacco et al. (2009) reported reduced ankle mobility during stance and ankle plantarflexion during push-off were accompanied by higher peak pressure and pressure-time integral values at the forefoot in patients with diabetic neuropathy with the authors also confirming an inadequate foot rollover associated with the smaller range of motion. More recently, Macklin et al. (2012) reported that tightness in the gastrocnemius muscles and a limited range of motion at the ankle were accompanied by a significant increase in peak plantar pressure and maximum force exerted on the forefoot in adults. Furthermore, Alentorn-Gali et al. (2013) reported relationships between lower angles of ankle plantarflexion and increased maximum plantar pressures under the 2nd metatarsal region in adults.

Consequently, tightness in the calf muscle resulting in reduced ankle mobility that facilitates an inadequate foot rollover may be a possible means to explain the relationship between reduced plantarflexion and loading at the 2-5MTPJ evident in the overweight and obese children from this research and suggests that joint kinematics can impact the foot loading characteristics of these children. This is supported by Bowling et al. (2011) who reported reduced ankle plantarflexion would facilitate an inadequate foot rollover during gait that in turn would increase the contribution of the metatarsals during push-off, due to an inability to fully engage the toes.

Significantly greater angle of ankle dorsiflexion during mid-swing was also reported in the overweight and obese children when compared to normal weight participants. Dorsiflexion of the ankle assists toe clearance during SW (Levine et al. 2012) and increasing this angle may be a strategy adopted by the overweight and obese children to help with toe clearance and minimise the risk of tripping to maintain stability during walking. Increased dorsiflexion during mid-swing may also contribute towards the increased loading at the midfoot, evident in overweight and obese children, as attested by the significant relationship with normalised peak force at this site (Table 6.10, page 144). To the authors’ knowledge, this study is the first to report a relationship between ankle dorsiflexion during SW and foot loading at the midfoot in overweight and obese children; indicating that the position of the ankle prior to initial contact, potentially in combination with a flatter (planus) foot type, influences foot loading at this site. However, due to the exploratory nature of this work, the specific causative factors associated with this relationship cannot be confirmed. It would be beneficial for future work to consider the use of three-dimensional multi-segment foot models to provide advanced understanding of the multiple articulations and functional complexities of the foot and the relationship this has with lower limb kinematic gait patterns.

Altered sagittal plane ankle kinematics in the overweight and obese children was accompanied by altered sagittal plane hip kinematics in the obese children alone.

These children reported significantly reduced angle of hip extension in SS (-1.27^0) and TDS (-2.03^0) and significantly increased angle of hip flexion during TDS, prior to toe-off (3.39^0) relative to normal weight children (-9.48^0, -10.41^0 and -3.47^0 respectively) (Table 6.3, page 125). These changes accompanied by a reduced range of motion in the obese children (-2.03-34.87^0) relative to those of normal weight (-10.41-33.87^0) may explain the significantly slower walking speed and reduced step length reported in this cohort. This is supported by findings from previous research, which reported reduced hip extension to be associated with slower walking speeds and a shorter stride length in obese children and adults (Lai et al. 2008; Wabitsch et al. 2012).

Significantly greater hip flexion during TDS reported in the obese children may be a compensatory strategy to lower the centre of mass and increase dynamic stability prior to single-limb support (Coutts, 1999; Perry and Burnfield, 2010). However, greater hip flexion would require a backwards tilt of the pelvis (Bartel et al. 2006) that could result in the posterior displacement of the centre of mass and subsequently reduce stability during gait. This would place greater emphasis on the hip extensors, which maintain stability during single-limb support (Perry and Burnfield, 2010) and which subsequently may not provide the necessary strength to extend the hip during gait. Therefore, reduced hip extension in the obese children during stance may be indicative of a reduced ability to fully extend the hips due to the muscles working to maintain stability.

Excess adipose tissue deposited in the thigh, gluteal and lumbar region of the obese may mechanically obstruct movements at the hip and possible explain findings from the present study where significantly reduced hip extension during SS and TDS was reported in obese children. Reduced hip extension may also indicate tightness in the hamstring muscles, with previous studies reporting that obese children presented reduced hip range of motion and less flexible hamstrings than children of healthy weight (Jozwiak et al. 1997). Emerging from this finding is evidence to suggest that obese children present additional kinematic changes at the lower limb in comparison to those overweight, associated with greater body mass. Differences in the sagittal plane kinematics of the hip suggest children who are obese could be at risk of developing musculoskeletal pain, as reduced hip range of motion and hamstring flexibility alongside increased BMI have been identified as predictors of lower back pain in adolescents (Jones et al. 2005; Sjolie, 2004). As such earlier intervention in children who are overweight may be key to mitigating against this health co-morbidity.

Altered sagittal plane hip kinematics may also contribute towards increased loading at the 2-5MTPJ as attested by the significant relationship between minimum hip angle during TDS and normalised peak force at this site (Table 6.10, page 144). Previous research has demonstrated a link between hip function and foot loading with Mueller et al. (1994) reporting that reduced hip extension and increased hip flexion accompanied higher forefoot peak pressures in participants with peripheral neuropathy.

No significant group differences were identified in frontal and transverse plane movements at the hip, knee and ankle. These results are in agreement with Shultz et al. (2009) who reported no differences in frontal and transverse angular displacements between overweight and normal weight children. This suggests that weight bearing activities may result in similar frontal and transverse plane kinematics regardless of body mass and that changes in the kinematic patterns of walking in overweight and obese children are reflected more greatly in the sagittal plane. However, these results are in disagreement with those of McMillan et al. (2009, 2010) who reported that overweight children maintained greater knee abduction and hip adduction throughout stance compared with *“healthy weight”* children.

Analysis of the frontal plane motion curves for the hip (Figure 6.3, page 129) identified that obese children demonstrated increased peak hip adduction angles during IDS (5.45^0) and SS (7.43^0) when compared with normal weight children (3.89^0 and 5.78^0). In addition, frontal plane motion curves for the knee (Figure 6.3, page 129) revealed obese children demonstrated an abducted position throughout stance in contrast to the adducted position maintained in normal weight children. Hip adduction in combination with knee abduction places the knee in a greater valgus position, increasing the stresses placed upon the joint in the frontal plane, increasing the risk of lower extremity malalignment (Wabitsch et al. 2012). These findings are consistent with the view that children who are obese are at an increased risk of developing lower limb discomfort and/or pathology as a consequence of the altered frontal plane kinematic walking parameters (Taylor et al. 2006; Wearing et al. 2006) and underlines the importance of health professionals prescribing non-weight bearing or low impact physical activities, to minimise stresses imposed upon the lower limb, as part of an intervention towards weight management for overweight and obese children.

This work had demonstrated differences in sagittal plane hip and ankle kinematics in overweight and obese children. Results indicate reduced hip extension and ankle plantarflexion during stance and increased ankle dorsiflexion during swing that limits their ability to advance the lower limb during gait and alters foot loading in these children during weight bearing activities. These findings highlight the need for earlier intervention in children who are overweight to mitigate against further health co-morbidities associated with obesity.

6.4.3 Kinetic Parameters during Walking

The third hypothesis for this phase of research was that overweight and obese children would demonstrate differences in peak joint moments at the hip, knee and ankle when compared to normal weight children. This research hypothesis was supported, with overweight and obese participants demonstrating greater sagittal, frontal and transverse plane absolute peak joint moments at the hip (flexor, extensor, adductor, internal and external rotator), knee (flexor, adductor, internal and external rotator) and ankle (adductor) in comparison to normal weight children. When absolute peak moment data was normalised to body mass, differences between groups were reversed. Overweight and obese children reported a significant reduction in peak joint moments across the three movement planes at the hip (extensor, adductor, internal and external rotator), knee (adductor, internal and external rotator) and ankle (dorsiflexor, plantarflexor, internal and external rotator) with all three phases of stance affected.

The increase in absolute joint moments are in agreement with previous research (Shultz et al. 2009) which reported significantly greater absolute peak moments at the hip, knee and ankle when comparing overweight to normal weight children. These findings emphasise the impact of increased body mass on the absolute force applied across the joints of the lower limb, indicative of higher stress during walking and increasing the risk of skeletal malalignment and injury in overweight and obese children. Greater hip flexion and extensor moments can increase forces on the femoral growth plate resulting in slipped capital epiphysis (Nasreddine et al. 2013), which is consistent with reports that consider this condition a health risk for obese children (Wabitsch et al. 2012). Furthermore, increased triplanar moments at the knee can contribute towards an earlier progression to osteoarthritis, compromise joint stability and increase the risk of genu valgus and varus conditions, both common in obese children (Taylor et al. 2006; Wearing et al. 2006).

Interestingly, Shultz et al. (2009) reported that differences in the absolute peak joint moments were largely eliminated once normalised to body mass; however, significantly greater normalised internal ankle dorsiflexor moments were still reported in the overweight children. These results are similar to those reported in this study where a significant reduction in normalised external dorsiflexor moments was observed in the overweight and obese children throughout stance. Ankle dorsiflexor moments have been considered critical in slowing the limb in the early stages of stance (Hreljac et al. 2001) and Shultz et al. (2009) commented that reduced dorsiflexor moments indicates greater difficulty in employing a breaking mechanism during gait. The authors also suggested that when carrying excessive body mass a person requires a greater breaking mechanism to remain upright. Although speculative, it appears that the overweight and obese children have difficulty with this breaking mechanism that may contribute towards diminished stability and warrants further investigation. Although the causative factors associated with these kinetic changes at the ankle cannot be confirmed from this work, it highlights a need for future research to consider the impact of muscular strength on ankle joint motion to provide evidence to inform clinical intervention.

Normalised sagittal and frontal plane kinetics differ to those reported by McMillan et al. (2009, 2010) where obese children demonstrated significantly higher normalised hip flexion moments during early stance, significantly lower normalised knee flexion moments at initial contact, as well as significantly lower normalised hip and knee abduction moments throughout stance when compared to *"healthy weight"* participants. However, McMillan et al. (2010) also reported significantly reduced hip extension and ankle plantarflexion moments during late stance in obese children, the results of which were confirmed in the present study. Reduced normalised ankle plantarflexor moments during late stance have also been reported in obese adults (Lai et al. 2008). Lai et al. (2008) suggested this, in combination with a lower 2nd peak vertical ground reaction force, represented a reduction in propulsive force generated by the ankle that limits push-off during walking relative to the carriage of greater body mass. The authors hypothesised that this might emphasise a weakness in the plantarflexor muscles as these are partial contributors to ankle joint moments in the sagittal plane. This is a possible mechanism to explain findings from the present study were reduced plantarflexion motion and moments were reported in the overweight and obese children. Interestingly, no differences were reported in the 2nd peak vertical ground reaction force when comparing obese, overweight and normal weight children in the present study (Table 6.6, page 133); highlighting overweight and obese children generate similar forces to propel their greater mass that may limit their ability to plantarflex and push-off during walking. McMillan et al. (2010) proposed that a decreased push-off by the ankle would likely require increased contributions at other joints and it is possible that the increased hip flexion angle during TDS, evident in the obese children in this study, is a mechanism to pull the limb into swing rather than push it through the plantarflexors.

Reduced hip extensor angles and moments during TDS may compromise ankle plantarflexion during gait, with reduced hip extension angle and moments reported alongside reduced ankle plantarflexion angle and moments in the overweight and obese children. Several authors have suggested greater difficulty in achieving ankle plantarflexion with the hip flexed due to the centre of mass being posterior to the forefoot (Bartel et al. 2006; Pease et al. 2005), thereby increasing the need to transfer weight from the rearfoot which requires greater force from the gastrocnemius and soleus muscles. This may also increase the emphasis on the 2-5MTPJ as a weight bearing structure during push-off, as reduced ankle plantarflexion would facilitate an inadequate foot rollover during gait that in turn would increase the contribution of the metatarsals, due to an inability to fully engage the toes resulting in the increased loading at this site evident in the overweight and obese children This is supported by the significant relationship between minimum hip and ankle moments during TDS and normalised peak force at the 2-5MTPJ (Table 6.11, page 145) and supports the view that joint moments can impact foot loading characteristics in obese children (Dowling et al. 2001; Hills et al. 2002).

Significantly reduced internal and external rotation moments at the hip, knee and ankle were reported in overweight and obese children relative to those of normal weight, with all phases of stance affected. Further kinetic changes were also demonstrated in the obese children alone with significantly reduced hip and knee adduction moments during SS; hip external rotator moments during SS and internal rotator moments during TDS, knee external rotator moments during IDS and TDS and ankle internal and external rotator moments during IDS and TDS also reported. These results were surprising when it is considered that no significant group differences were reported in the frontal and transverse plane kinematic parameters and may underline an adaptation that promotes a joint protection strategy. Runhaar et al. (2011) reported that obese individuals reduced their walking speed and altered lower limb kinematics to lessen loads on their joints. Consequently it is possible that the slower speeds of walking evident in the overweight and obese children was a strategy to reduce the force on the joint of the lower limb, rather than maintain stability during walking.

Andrews et al. (1996) and Runhaar et al. (2011) also reported that greater out-toeing of the foot was associated with decreased knee adduction moments relative to body weight (evident in the obese children of this study) because it shifts the force vector closer to the knee joint. This action could introduce a rotational malalignment that subsequently leads to cartilage degeneration in the affected joints increasing the risk of developing osteoarthritis (Andriacchi and Mundermann, 2006). This may further evidence to suggest that childhood obesity is associated with biomechanical change to the movement patterns of the lower limb and that obese children could be at an increased risk of developing further musculoskeletal dysfunction in comparison to overweight children and as such earlier intervention is required. However, further longitudinal work is required to determine whether altered frontal plane knee joint kinetics in obese children supports a precursor to joint dysfunction in order to provide the necessary evidence to advance care provision.

This phase of work provides evidence that overweight and obese children exhibit differences in the kinetics of the lower limb during walking relative to normal weight children. These changes emphasise the impact of increased body mass on the absolute force applied across the joints of the lower limb, indicative of higher stress that may predispose these children to lower extremity musculoskeletal injury. These results again identify a change in function at the hip and ankle with a reduced capacity to extend the hips that may then limit the ability to plantarflex and push-off through the ankle during gait. Differences in overweight children further compounds this problem and highlights that changes in joint kinetics may be associated with smaller gains in body mass than first thought.

6.4.4 Relationships between Characteristics of Foot Loading and the Kinematic and Kinetic Biomechanics of the Lower Limb during Walking

The final hypothesis proposed that a relationship would be found between plantar foot loading and joint kinematic and kinetics of the lower limb in overweight and obese children. This data supports the research hypothesis with relationships between normalised peak force at the MID and 2-5MTPJ and significant between-group kinematic and kinetic parameters reported in overweight and obese children.

The results indicate that normalised peak force at the MID was significantly correlated with reduced angles of hip extension during SS and increased angles of ankle dorsiflexion during mid-swing in overweight and obese children (Table 6.10, page 13744). In addition, normalised peak force at the 2-5MTPJ was significantly correlated with reduced angles and moments of hip extension and ankle plantarflexion during TDS (Tables 6.10, page 144 and 6.11, page 145). To this author’s knowledge, these relationships have not been previously reported in overweight and obese children; indicating that functional changes at the hip and ankle may result in altered foot loading patterns at the MID and 2-5MTPJ in overweight and obese children, the results of which warrant further investigation. Although the specific causative factors associated with these relationships cannot be confirmed, these results could be used as a foundation to inform clinical care; providing evidence to support the use of plantar pressure assessment in predicting changes to the biomechanical movement characteristics of the lower limb.

Linear regression was undertaken to establish whether these relationships form a basis for prediction to determine whether the foot loading characteristics of overweight and obese children can predict biomechanical differences in lower limb kinematic and kinetic gait patterns. Normalised peak force at the MID predicted 65% of the variance in increased dorsiflexion angle during mid-swing (p<0.05, Table 6.12, page 146). Furthermore, normalised peak force at the 2-5MTPJ predicted 69% of the variance in the lower angles of hip extension and ankle plantarflexion and lower hip extension and ankle plantarflexion moments during TDS in overweight and obese children (p<0.01, Table 6.13, page 147). These results provide evidence as to the use of plantar pressure assessment in predicting changes in lower limb kinematic and kinetic walking patterns of overweight and obese children to help recognise those likely at risk of developing joint dysfunction. These results could be used to inform clinical care, as due to the cost and complexity of three-dimensional gait analysis this resource is often not available in most therapy clinics and does not reflect the assessment commonly undertaken in clinics or in a patients home (Coutts, 1999). Plantar pressure assessment offers a cheaper and more practical alternative in the first line of clinical assessment when assessing lower limb function in overweight and obese children; thereby potentially increasing the access to clinical services for this cohort. Children diagnosed as overweight or obese children could be screened using plantar pressure assessment with the aim to assess foot loading and predict changes in the biomechanical function of the lower limb.

6.5 Chapter Summary

Consideration of the temporal-spatial and lower limb kinematic and kinetic walking patterns identified that differences exist between obese, overweight and normal weight children. Comparative analysis indicated that:

- Overweight and obese children walked with a significantly slower velocity and reduced step length in comparison to normal weight children.

- Overweight and obese children demonstrated significantly reduced ankle plantarflexion during TDS and early in SW and significantly greater ankle dorsiflexion during mid-swing when compared to normal weight children.
- Obese children also demonstrated significantly reduced hip extension during SS and TDS and significantly increased hip flexion late in TDS and at the start of SW relative to normal weight children.
- Overweight and obese children demonstrated significantly reduced lower limb normalised joint moments across the three movement planes, with different periods of stance affected.
- Further changes were evident in obese children alone with significantly reduced normalised hip and knee adduction moments during SS, knee abductor moments during TDS, hip external rotator moments during IDS and internal rotator moments during TDS, knee internal rotator moments during IDS and external rotator moments during TDS and ankle internal and external rotator moments during IDS and TDS reported.

Analysis of the relationship between foot loading and significant between-group kinematic and kinetic walking parameters in overweight and obese children identified:

- Normalised peak force at the MID predicted 65% of the variance in maximum ankle angle during SW.
- Normalised peak force at the 2-5MTPJ predicted 69% of the variance in minimum hip and ankle angle and minimum hip and ankle moments during TDS.

These results provide evidence that obesity may have implications on the function of the lower limb and that functional changes are also evident in overweight children; supporting earlier intervention to mitigate against health co-morbidities associated with childhood obesity. In addition, a relationship between foot loading and lower limb kinematic and kinetic gait parameters in overweight and obese children has emerged; highlighting the potential of plantar pressure assessment in predicting changes to the biomechanical movement characteristics of the lower limb in this cohort. The final chapter will look to summarise the results from Chapters 4, 5 and 6, detailing the impact of overweight and obesity on foot loading and lower limb biomechanical movement characteristics in children.

CHAPTER SEVEN: THESIS SUMMARY

Current literature detailing the definition, prevalence and assessment of childhood obesity, together with the impact of childhood obesity on foot structure, foot loading and lower limb biomechanical parameters of gait were reviewed (Chapter Two, page 6). It was identified that obesity in children can have a detrimental influence on the structure and function of the paediatric foot. It was also suggested that obese children display altered temporal-spatial and lower limb kinematic and kinetic movement patterns that may predispose them to musculoskeletal pain and injury. However, existing research often fails to include overweight children within its sample and further work is essential as early prevention and intervention may be key to mitigating against health co-morbidities associated with childhood obesity. Furthermore, few studies have presented a comprehensive examination of foot loading or three-dimensional gait analysis, using established reliable protocols; and as such the full impact of overweight and obesity on the paediatric foot and lower limb is poorly understood.

It was the overall aim of this research to advance understanding of foot function and lower limb biomechanical movement characteristics in children; analysing differences between obese, overweight and normal weight children. Detecting functional changes to the foot and lower limb associated with increased body mass could advance understanding of mechanisms leading to musculoskeletal co-morbidities; whilst providing evidence to inform current practice in the prevention and treatment of the maladaptation in the lower extremities of overweight and obese children. It will also provide key information for researchers and clinicians as to the use of plantar pressure assessment and three-dimensional motion analysis in evaluating foot loading and lower limb biomechanics in children. Prior to this it was important to investigate the reliability of measurement protocols for the assessment of anthropometry, foot loading and lower limb temporal-spatial, kinematic and kinetic gait parameters in children.

Measurement protocols for the assessment of body mass status using BMI and skinfold measures, foot loading characteristics via plantar pressure assessment and lower limb temporal-spatial, kinematic and kinetic gait parameters via three-dimensional motion analysis have been developed (Chapter Three, page 60). Within and between-session reliability of body mass, height and skinfold measures were assessed alongside peak pressure and peak force, normalised force and pressure-time and force-time integral measures across seven plantar regions of the foot in a group of typically developing children, aged 7 to 11 years. Additionally, within- and between-session reliability of triplanar kinematic and kinetic gait parameters at the hip, knee and ankle across multiple phases of the gait cycle were measured along with temporal-spatial parameters (Chapter Four, page 87). The results demonstrated:

- Measurements used for the assessment of body mass status were reliable.
- Plantar pressure assessment was reliable across all regions of the foot, excluding the 2nd-5th toes.
- Reliable temporal-spatial gait data of velocity, cadence, step length, step width and time spent in single- and double support.
- Reliable sagittal, frontal and transverse plane kinematic data of maximum and minimum joint angles and kinetic data of maximum and minimum external joint moments at the hip, knee and ankle during IDS, SS, TDS and SW.

This work demonstrated that the collection of reliable foot loading data within a single session and between two sessions is possible in typically developing children; with few studies having considered the reliability of protocols for the assessment of plantar pressure data in a paediatric population. The results suggest that most segments of the foot yield reliable data for the analysed variables of peak pressure, peak force, pressure-time integrals and force-time integrals with the exception of the lesser toes. Furthermore, this work contributes to evidence underpinning the reliability of clinical measures for the assessment of body mass status and lower limb temporal-spatial, kinematic and kinetic gait parameters in children.

Following this, the plantar foot loading characteristics of obese, overweight and normal weight children, aged 7 to 11 years, during barefoot level walking were compared and the use of cluster analysis in identifying differences in foot loading of these children was evaluated (Chapter Five, page 100). Between-group analysis indicated:

- Overweight and obese children generated significantly greater peak and temporal characteristics of foot loading at the midfoot and 2nd-5th metatarsals in comparison to normal weight children. Obese children also demonstrated significant increases at the lateral and medial heel relative to normal weight children.
- When peak force was normalised to body mass a significant increase at the midfoot and 2nd-5th metatarsals was still evident in the overweight and obese children relative to those of normal weight.

Functional foot type classification through cluster analysis added further insight to these findings and indicated that:

- The majority of overweight (77.3%) and obese (86.4%) children loaded the plantar surface of their foot differently in comparison to normal weight children; generating significantly greater peak and temporal characteristics of foot loading at the lateral and medial heel, midfoot and 2-5th metatarsals as well as significantly greater normalised peak force values at the midfoot and 2nd-5th metatarsals.

This study demonstrated differences in foot loading characteristics of overweight children relative to their normal weight peers; presenting detailed data for specific regions of the foot using reliable methods and conforming to international guidelines (Giacommozzi, 2011). Emerging from this work is the view that overweight and obese children display similar patterns of plantar foot loading and changes (associated with increased body mass) occurred earlier than previously documented; associated with a smaller increase in body mass than first thought. This finding reinforces the view that early intervention and consideration in overweight children is required to mitigate against the impact of obesity on the paediatric foot.

These findings suggest a change in the biomechanical function of the paediatric foot, indicative of elevated levels of loading acting upon the soft-tissue and joint structures of the heel, midfoot and 2nd-5th metatarsals in overweight and obese children. This supports the view that these children could be at risk of developing foot discomfort and/or pathology as a consequence of the increased and prolonged forces upon acting upon the immature musculoskeletal structure of the foot. Elevated and prolonged patterns of loading at the midfoot are indicative of a flatter (planus) foot type. In addition, the increased loading of the 2nd-5th metatarsals is suggestive of a hypermobile 1st metatarsal that is unable to provide the necessary support during propulsion; highlighting the importance of this region as a weight-bearing structure during push-off.

Finally, differences in the plantar foot loading characteristics of obese, overweight and normal weight children were confirmed through cluster analysis, with two heterogeneous patterns being identified. This work provides early evidence for the use of cluster analysis in identifying groups of children with similar foot loading characteristics to inform intervention strategies with the aim of reducing high regional plantar pressures and forces that could then be used as a foundation to inform clinical care. Due to similarities in their foot loading patterns, overweight and obese children could be prescribed the same group-specific intervention with the expectation that it would reduce elevated foot loading. As a result further longitudinal work is required to determine whether overweight and obese children would benefit from footwear that provides adequate cushioning to assists with shock absorption and/or foot orthoses that optimise foot function during common daily activities.

Following the study of foot loading, the temporal-spatial and triplanar kinematic and kinetic biomechanical movement characteristics of the hip, knee and ankle were evaluated in a group of obese, overweight and normal weight children, aged 7 to 11 years (Chapter Six, page 120), with comparative analysis revealing:

- Overweight and obese children walked significantly slower and with a significantly reduced step length relative to normal weight children.
- Overweight and obese children walked with significantly reduced ankle plantar flexion during TDS and at the start of SW in addition to significantly greater ankle dorsiflexion during mid-swing when compared to normal weight children.
- Obese children walked with significantly reduced hip extension during SS and TDS and significantly increased hip flexion at the start of SW relative to normal weight children.
- Overweight and obese children demonstrated significantly reduced hip extensor moments during TDS, ankle dorsiflexor moments during IDS, SS and TDS, ankle plantarflexor moments during TDS, hip internal rotator moments during SS, knee internal rotator moments during SS and TDS and internal rotator moments at the ankle during IDS and SS.
- Obese children also demonstrated significantly reduced normalised hip and knee adduction moments during SS, knee abductor moments during TDS, hip external rotator moments during IDS and internal rotator moments during TDS, knee internal rotator moments during IDS and external rotator moments during TDS and ankle internal and external rotator moments during IDS and TDS.

Relationships between characteristics of foot loading and lower limb kinematic and kinetic walking patterns in overweight and obese children were also explored in this phase of work, with the data revealing:

- Normalised peak force at the midfoot predicted 65% of the variance in maximum ankle angle during SW.
- Normalised peak force at the 2nd-5th metatarsals predicted 69% of the variance in minimum hip and ankle angle and minimum hip and ankle moment during TDS.

This study demonstrated marked differences in the lower limb biomechanical gait characteristics of overweight children when compared to those of normal weight. These findings also identified similarities in the temporal-spatial and lower limb kinematic and kinetic walking patterns in overweight and obese children; suggesting these changes occur earlier than previously reported and with a smaller increase in body mass than first thought. Additional changes in the biomechanical function of the hip, knee and ankle were reported in the obese children in comparison to those overweight, associated with greater body mass. Emerging from this finding is evidence to suggest obese children present added kinematic and kinetic change at the lower limb, associated with greater body mass, which indicate they could be at risk of developing musculoskeletal pain and as such earlier intervention in children who are overweight is required to mitigate against further health co-morbidities.

Altered temporal-spatial gait characteristics were evident in overweight and obese children, indicative of a slower, safer more tentative walking pattern; suggesting that overweight and obese children have a greater degree of instability during gait and the differences reported in velocity and step length were compensatory measures to maintain stability during walking. Reduced ankle plantarflexion angles and moments towards the end of TDS during the transition into SW in the overweight and obese children may also be indicative of underlying muscular weakness in the plantarflexors of overweight and obese children, relative to their greater body mass, that compromise the ability of the ankle to push-off and advance the lower limb during walking.

Obese children also presented altered hip kinematic and kinetic characteristics when compared to normal weight participants. Significantly greater hip flexion during TDS reported in the obese children may be a strategy to lower the centre of mass to increase dynamic stability prior to single-limb support. However, greater hip flexion would require a backwards tilt of the pelvis that could result in the posterior displacement of the centre of mass and subsequently reduce stability during gait. This would place greater emphasis on the hip extensors, which maintain stability during single-limb support and which subsequently may not provide the necessary strength to extend the hip during gait. Therefore, reduced hip extension in the obese children during stance may be indicative of a reduced ability to fully extend the hips due to the muscles working to maintain stability.

Relationships between normalised peak force at the midfoot and 2nd-5th metatarsals and significant between-group kinematic and kinetic parameters were reported in overweight and obese children. Furthermore, linear regression established these relationships form a basis for prediction. These results provide important information as to the use of plantar pressure assessment in predicting differences in lower limb kinematic and kinetic walking patterns of overweight and obese children to help recognise those likely to demonstrate altered functional characteristics and identify children at risk of developing joint dysfunction. These results could be used to inform clinical care, as due to the cost and complexity of three-dimensional gait analysis this resource is often not available in most therapy clinics. Plantar pressure assessment offers a cheaper and more practical alternative in the first line of clinical assessment when assessing lower limb function in overweight and obese children; thereby potentially increasing the access to clinical services for this cohort. Children diagnosed as overweight or obese children could be screened using plantar pressure assessment with the aim to assess foot loading and predict biomechanical differences in the function of the lower limb.

A greater understanding into the implications of overweight and obesity on foot loading and lower limb biomechanical gait patterns of children has emerged from this work. However, there are several limitations and avenues for further research that will enhance our understanding of the consequences of excessive body mass on the foot and lower limb musculoskeletal and locomotor systems in children, particularly during weight bearing tasks. Only once a comprehensive understanding has been established can interventions be developed to provide the necessary evidence to advance care provision for these children.

7.1 Limitations and Further Research

7.1.1 Sample Issues

The recruitment of 100 children from a multi-ethnic population (Chapter Five, page 100) and a sub-group of 45 multi-ethnic children (Chapter Six, page 120) provide a strong foundation for a normative database for our gait laboratory. However, external validity is limited as the sample is small to draw inferences to the wider population. Further work may wish to address the complex issue of ethnicity and ensure future studies are adequately powered in order to consider the impact of this and increased body mass on paediatric foot and lower limb function. Previous research has demonstrated differences in foot loading and lower limb gait patterns when comparing Hispanic (Solano et al. 2008), Maori (Gurney et al. 2012) and African American (Blanco et al. 2012) adults to their Caucasian counterparts; however, subsequent data in children is lacking.

7.1.2 Assessment of Childhood Obesity

It has been suggested that since obesity is by definition excess body fat, childhood obesity should be defined on the basis of a body fatness measurement (Reilly, 1998, Reilly et al. 2000). Due to the field based nature of this research, participants were classified in accordance with their Body Mass Index Standard Deviation Score (BMI-SDS). This, however, measures weight adjusted to height, matched to age and gender reference values and not body fat mass. This has the potential to lower the specificity of this measure and mislabel children of a short-compact build as overweight or obese even if they do not have excess adiposity (body fatness). Consequently, future work should consider the use of laboratory based measures to define overweight and obesity in children by adiposity (i.e. air displacement plethysmography, bioelectrical impedance analysis).

Defining childhood overweight and obesity is further complicated by ethnicity. Previous research has reported differences between ethnic groups in their BMI-percentage body fat relationship (Deurenberg et al. 1998; Deurenberg and Deurenberg-Yap, 2001). The BMI-SDS represents the number of standard deviations a child is from population specific reference standards. This research adopted the 1990 British Growth Reference data, which may mislabel participants from different ethnic backgrounds. Future work may wish to consider the use of ethnic specific BMI age and gender related reference standards to diagnose paediatric overweight and obesity as have been developed for Indian (Virani, 2011), Sri Lankan (Wickramasinghe et al. 2013) and Pacific Island (Duncan et al. 2010) children. However, there is currently insufficient evidence and a lack of consensus regarding this issue and further work is needed to differentiate the role of BMI cut-offs in categorising obesity across ethnic groups.

7.1.3 Study Design and Methods

Due to the cross-sectional study design, this research was unable to establish relationships between increased body mass and altered foot and lower limb function in children. Further longitudinal research is required to investigate the consequence of physical growth on foot and lower limb function in overweight and obese children across a broader age range; with a particular focus on identifying the age at which functional changes (as a result of increased body mass) become apparent.

The analysis of absolute within- and between-session reliability in the data was assessed via the Coefficients of Variation (CoV). This measure of absolute reliability has previously been shown to be an accepted method for determining reliability within and between testing sessions for comparisons between variables expressed in different units (Atkinson and Nevill, 1998; Bruton et al. 2000); however, due to the absence of agreed criterion for the interpretation of CoV values, it was difficult to comment upon the variability and clinical relevance of the values derived in this study.

Previous research suggests an analytical goal of the CoV being ≤10% in adult populations (Atkinson and Nevill, 1998; Stokes, 1985); however, the extrapolation of this to the paediatric population maybe invalid, in that children's gait is associated with increased variability. It may have been prudent to consider other techniques to assess absolute reliability, such as the Standard Error of Measurement (SEM). The SEM reflects the standard deviation of measurement error (an index of the expected variation in observed scores due to measurement error) and provides a direct measure of measurement accuracy, expressed in the actual units of measurement, making its interpretation easier (i.e. the smaller the SEM the greater the reliability) (Atkinson and Nevill, 1998; Bruton et al. 2000). The use of SEM allows researchers to determine a range of scores, within which the true score may fall; as a result, researchers can assume a value does not represent a true change if it falls within the calculated range of measurement error. However, there is a lack of consensus regarding the determination of reliable measurement protocols for the assessment of foot loading and gait parameters in children with further work warranted in this area.

Limitations with the use of the TekScan MatScan® may have affected the accuracy of the data and limited comparison between obese, overweight and normal weight children. Zammit et al. (2010) previously discussed limitations with the use of this system, including factors such as the manual masking procedure for determining individual foot segments, as well as the relatively low sampling frequency (40 Hz) and spatial resolution (1.4 sensors/cm^2); all of which would affect the validity of this system and limit its ability in accurately isolating small regions of the foot, as seen in children. Future work should consider the use of a plantar pressure system with an increased sampling frequency and spatial resolution when analysing foot loading characteristics of children.

The causative factors associated with overweight and obesity and changes to foot loading and lower limb gait biomechanics cannot be confirmed from this work. It would be beneficial for future work to consider the use of three-dimensional multi-segment foot models to provide advanced understanding of the multiple articulations and functional complexities of the foot with particular attention given to establishing relationships between increased body mass, plantar foot loading, foot structure and the development of musculoskeletal pathology. Assessment of muscular strength and EMG activity, particularly of the hip extensors and ankle plantarflexors, would also have enhanced the interpretation of the lower limb biomechanical data in this research. Future work investigating the link between body mass, lower limb muscular strength and lower limb gait parameters would further our understanding as to the implications of childhood overweight and obesity on the lower limb musculoskeletal system during functional tasks.

The changes to foot loading and lower limb gait biomechanics (associated with overweight and obesity) may also have existed due to differences in gait velocity when comparing overweight and obese children to their normal weight peers. Rosenbaum et al. (2013) demonstrated that changing gait speed altered maximum force, peak pressure and force-time integrals across 10 planter regions in twenty typically developing children (8 ± 2 yrs); with an increase in gait speed associated with an increase in the peak and reduction in the temporal characteristics of foot loading respectively. In addition, previous research has reported a change in gait speed significantly impacted upon ankle joint kinematics in healthy children (van der Linden et al. 2002). Controlling for gait speed in a paediatric population, whilst also striving to achieve a representative gait pattern is difficult, as increased gait asymmetry and an alteration in normal lower limb biomechanical gait parameters have been reported in children when precise gait instructions were given (Bosh et al. 2010; Goble et al. 2003). Furthermore, current consensus regarding the control of gait velocity when comparing foot loading and lower extremity gait parameters in obese, overweight and normal weight children is not clear, with differences reported in studies both matching gait velocity (Dowling et al. 2004; McMillan et al. 2010: Shultz et al. 2009) and allowing participants to select a natural, self-determined walking speed (Yan et al. 2013; McMillan et al. 2009; Mickle et al. 2006). Due to the field based nature of this study and the collection of data across multiple sites, a pragmatic decision was made and gait speed was not controlled; however, future work should consider matching participants on gait velocity, to account for any differences in foot loading and lower limb mechanics that may exist due to differences in walking speed.

Finally, whether the functional changes to the foot and lower limb, as demonstrated in this research, were associated with pain, discomfort and musculoskeletal dysfunction to deter the overweight and obese children from participating in physical activity, and thereby perpetuating the cycle of obesity and exacerbating foot and lower limb problems, requires further investigation.

7.2 Clinical Implications

The present study has demonstrated differences in the plantar foot loading characteristics and lower limb biomechanical walking patterns of obese, overweight and normal weight children, aged 7-11 years. This data contributes towards the evidence detailing the implications of overweight and obesity on the paediatric foot and lower limb biomechanical movement characteristics in children, offering the following:

- Advances our understanding on lower extremity biomechanics and the impact of overweight and obesity on the hip, knee, ankle and feet of children.
- Highlights that smaller increases in body mass, than previously reported, may influence foot loading and the temporal-spatial, kinematic and kinetic walking patterns of children. Consequently, clinical intervention may be warranted earlier to mitigate against further health co-morbidities.
- Demonstrates a change in biomechanical function of the paediatric foot and lower limb in overweight and obese children in regards to altered loading patterns at the heel, midfoot and 2nd-5th metatarsals and altered temporal-spatial, kinematic and kinetic walking patterns respectively.

- Supports the view that children who are overweight and obese could be at risk of developing foot discomfort and/or pathology, such as pes planus or fractures of the 2nd-5th metatarsals; as well as increasing the likelihood of developing long-term orthopaedic conditions such as slipped capital epiphysis or Blouts disease.
- Offers research to inform current care provision for overweight and obese children:
    - Emphasises the need for both health professionals and footwear manufacturers to encourage obese and overweight children to wear footwear that provides adequate cushioning to assists with shock absorption in order to minimise excessive plantar foot loading.
    - Highlights the need for intervention to optimise foot function to alleviate increased pressures and forces at the midfoot and 2nd-5th metatarsals and provide added stability during weight bearing activities, possibly through the use of foot orthoses.
    - Underlines the importance of health professionals prescribing non-weight bearing or low impact physical activities, to minimise stresses imposed upon the foot and lower limb, as part of a weight management program for overweight and obese children.
    - Demonstrates the potential use of plantar pressure assessment in predicting biomechanical differences in lower limb walking patterns of overweight and obese children to help identify those likely to demonstrate altered functional characteristics which support a possible precursor to joint dysfunction.

This study established protocols to reliably determine body mass status, plantar foot loading and lower limb biomechanical movement characteristics in a multi-ethnic sample of children, aged 7 to 11 years. Increased body mass was associated with a change in the biomechanical function of the paediatric foot and lower limb during gait. Key relationships that formed a basis for prediction were also established between plantar foot loading at the midfoot and 2nd-5th metatarsals and significant between-group kinematic and kinetic walking parameters at the hip and ankle in overweight and obese children. This furthers our understanding as to the implications of childhood overweight and obesity on foot loading and lower limb gait patterns; whilst providing useful information for researchers and clinicians as to the use of plantar pressure assessment tools and three-dimensional motion analysis in evaluating lower limb function in children. This underpins the need for further longitudinal research looking at the prevention and treatment of maladaptations in the lower extremities of overweight and obese children.

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APPENDICES

APPENDIX 1: ETHICAL APPROVAL

Dr Stewart Morrison
School of Health and Bioscience
Stratford

ETH/08/94

19 June 2015

Dear Dr Morrison,

Application to the Research Ethics Committee: The Effects of Obesity on the Biomechanical Movement Characteristics of Children Aged 7-11 Years (S Cousins)

I advise that Members of the Research Ethics Committee have now approved the above application on the terms previously advised to you. The Research Ethics Committee should be informed of any significant changes that take place after approval has been given. Examples of such changes include any change to the scope, methodology or composition of investigative team. These examples are not exclusive and the person responsible for the programme must exercise proper judgement in determining what should be brought to the attention of the Committee.

In accepting the terms previously advised to you I would be grateful if you could return the declaration form below, duly signed and dated, confirming that you will inform the committee of any changes to your approved programme.

Yours sincerely

Debbie Dada
Administrative Officer for Research
d.dada@uel.ac.uk
02082232976

Research Ethics Committee: ETH/08/94/0

I hereby agree to inform the Research Ethics Committee of any changes to be made to the above approved programme and any adverse incidents that arise during the conduct of the programme.

Signed:...   Date: ....

Please Print Name:

APPENDIX 2: INVITATION LETTER

Stratford Campus, Romford Road, Stratford, London, E15 4LZ

Dear Parent/Guardian

Your child's school has been invited by the University of East London to take part in some exciting research that investigates the effects of walking on the feet and legs of developing children (aged 7-12).

All pupils have been invited to participate within this study; hence we are sending this invitation letter to all parents with children in this school year.

Enclosed with this letter is an information sheet which details the research and what would be required of your child. We would be extremely grateful if you could find a few minutes to read this information. If you are happy for your child to participate then please sign the consent form (also included, last document in the wallet) and give it to your son/daughter to return to school.

Your child has also been given a talk on this study and has been provided with an information pamphlet.

In order to participate, your son/daughter will also have to give their consent.

We would greatly appreciate your co-operation and if there are any questions please do not hesitate to contact me via the details provided on the information sheet.

Many Thanks.

Stephen Cousins
Lecturer in Sport and Exercise Science, University of East London

APPENDIX 3: STUDY INFORMATION SHEET

Stratford Campus, Romford Road, Stratford, London, E15 4LZ

University Research Ethics Committee

If you have any queries regarding the conduct of the programme in which you are being asked to participate please contact the Secretary of the University Research Ethics Committee: Ms D Dada, Administrative Officer for Research, Graduate School, University of East London, Docklands Campus, London, E16 2RD (Tel: 0208 223 2976; e-mail: d.dada@uel.ac.uk).

Principal Investigators

Mr Stephen Cousins, BSc, MSc and Dr Stewart Morrison, PHD
University of East London, Stratford Campus, University House, Romford Road, Stratford, London. E15 4LZ
E-mail: s.d.cousins@uel.ac.uk, s.c.morrison@uel.ac.uk; Tel: 0208 223 4515 (Stephen Cousins), 0208 223 2679 (Dr Stewart Morrison)

Project Title

"The Effects of Walking on the Biomechanics of the Legs, Muscles and Feet in Children Aged 7-11 Years"

The purpose of this letter is to provide you with the information that you need to consider in deciding whether to allow your child to participate in this study.

We would like to invite your child to participate in a research project undertaken by the School of Health and Bioscience at the University of East London. The research has the approval of the Head Teacher of your child's school and we will be working closely with schools to provide information regarding this research project.

This form provides you with the information about the study and informs you of how your child's privacy will be protected and what your child's involvement will be if you agree they can take part.

Your child's participation is voluntary and you can withdraw your child from the research at any time without giving any reason and this will not affect the status of your child's medical care or legal rights. If you choose not to participate at all in this study you will not be penalised or lose any benefits to which you would otherwise be entitled.

We hope you will give your consent for your child to participate in this valuable research. If you have any questions or would like to discuss this further please contact Stephen Cousins on 0208 223 4515 (work) or 07912304618 (mobile).

Project Description

How can my child be included?
To participate in the research your child needs to be aged between 7 and 11 years old. The research will be undertaken by one PHD student and one assistant, both from the University of East London.

What is the study looking at?
The aim of the research is to investigate how walking affects the legs, muscles and feet in a developing child. This will be done using specialist machine (described in greater detail later) connected to a computer.

The research itself is broken down into two different phases:

i. **Phase 1 – What is involved?/What will my child have to do?/How long will it take?**

This phase will involve monitoring the daily physical activity levels of your child over the course of one week. With your help your child will need to complete a simple questionnaire, known as the International Physical Activity Questionnaire on a daily basis over the course of the week). They will also be required to wear a small device for the week, known as an Actiband Accelerometer, which will monitor the amount of daily activity performed by your child (i.e. walking, running). These devices are small, light-weight instruments, worn at the right hip, which will pose no harm or discomfort to your child. At the end of the week you simply return to device to the Principal Investigator. Also during this phase we will measure the thickness of your child's skin using skinfold callipers. These devices are designed to measure the thickness of their skin at specific sites on the body by taking a pinch of skin and holding it between the calliper heads. The sites selected for this study are the upper arm and lower leg. All measurements will be taken by someone of the same gender as your child. Data collection will take place behind a medical screen to maintain the privacy of your child. If yourself or your child is not happy with this procedure taking place (you/they are in no way obliged to do so) then the measurements will not be taken, but your child will still be more than welcome to continue their participation in the study at no disadvantage to themselves what-so-ever.

During this phase the study will investigate the effects of walking on the feet of your child. This part of the study will look to recruit between 50-100 subjects. Your child will be required to walk barefoot across a special mat (Matt-Scan Walk Mat) no more than ten times. This phase will take place at your child's school, during a PE lesson, and will take about one hour. Your child will be able to rest whenever they want to and they will only need to attend once.

During this phase of the research your child's teacher will be present and some of their classmates. However you are also invited to be present during the testing, if you do so wish.

ii. Phase 2 – What is involved?/What will my child have to do?/How long will it take?

All participants from Phase 1 will be invited to take part in Phase 2. This phase will look to investigate the effects of walking on the legs and muscles of your child by using two special pieces of equipment called the VICON Motion Analysis and EMG systems and will take place in special laboratories at the University of East London.

Your child will be asked to walk across a room containing ten specially designed cameras. These cameras are designed to analyse the way an individual's walks three-dimensionally. They will also have small markers and pieces of equipment attached to their skin and muscles. The effects of walking on your legs and muscles will then be recorded on a computer. This part of the research will take a maximum of 1hour and 30minutes. Any travelling costs, as a result of yours or your child's attendance will be fully reimbursed and refreshments will also be provided throughout this phase of the testing at no cost to yourself. Please let us know if you intend to bring additional siblings so we can cater for these as well. Again your child will be able to rest whenever they want to and will only need to attend once.

The same investigators that were present in Phase 1 will perform this phase of the research project. Your attendance would also be greatly appreciated during this phase in order for your child to participate; any other children in the family are also more than welcome.

Are there any possible discomforts or risks?

- This study may include risks that are unknown at this time.
- During Phase 2 of the study having the small pieces of equipment attached to the skin and muscles of your child, might feel a little odd for them, but it will not hurt and they can be removed easily.
- If your child does ever feel any pain, has strange feelings in their legs or suffers an injury whilst participating in any part of this study you must let the Principal Investigator (listed on the 1st page of this document) know immediately.

<u>Confidentiality of the Data</u>

(Who will know about the results?)

Information collected about your child will be stored in computers with security passwords. Only the primary researcher and his research team have access to review these research records, and they will protect the confidentiality of these records. Otherwise the research records will not be released without your permission unless required by law or a court order. If the results of this research are published or presented at scientific meetings, no child's identity will be disclosed.

On completion of this research project data will be stored in locked filing cabinets or in computers with security passwords for 10 years, for its potential use in deriving published articles or presentations at scientific conferences. After 10 years all data (paper based and computer stored) will be destroyed manually.

Location and Remuneration

(Where do I need to go and will it cost me anything?)

Phase 1 of this study will take place at your child's school, during a normal school day. In Phase 2, the machines are kept in London, at the University of East London, Romford Road, Stratford, London. All travelling expenses incurred, as a result of yours or your child's attendance will be fully reimbursed. Refreshments will also be fully provided at no cost to yourself. Please let us know if you intend to bring additional siblings so we can cater for these as well. A map, details of the closest underground, train, bus routes and parking will be given to you hopefully give consent for your child to participate.

Disclaimer

(Does my child have to take part?)

As previously stated, your child is not obliged to take part in this study, and you are free to withdraw them at any time during the testing. Should you choose to withdraw from the programme you may do so without disadvantage to yourself or your child and without obligation to give a reason.

If you have any further questions or would like to discuss any aspect of this research project in greater detail, please feel free to contact the Principal Investigator (via the contact details provided on the 1st page of this document).

APPENDIX 4: PARENTAL/GUARDIAN CONSENT FORM

UEL
University of
East London

Consent Form
(Parent/Guardian of child participant)

Consent to participate in an Experimental Programme Involving the Use of Human Participants

"The Effects of Walking on the Biomechanics of the Legs, Muscles and Feet in Children Aged 7-11 Years"

Name of Researcher: Stephen Cousins

Please Initial

1. I confirm I have read the information package dated . . . . relating to the above programme of research in which my child has been asked to participate and have had the opportunity to ask questions and been given a copy of this to keep. I understand what is being proposed and the procedures in which my child will be involved in have been fully explained to me. ☐
2. I understand my child's participation is voluntary and I have the right to withdraw my child at any time without being obliged to give a reason. This does not affect the status of my child's medical care or legal rights. ☐
3. I understand that my child's involvement in this study, and the particular data from this research, will remain strictly confidential. Only the researchers involved in the study will have access to the data. It has been explained to me what will happen to the data once the experimental programme has been completed. ☐
4. I hereby testify to being the child's lawful parent/guardian and agree for my child to participate in the above study. ☐

Child's Name:

Name of Parent/Guardian:

Signature:

Date:

Name of Researcher:

Signature:

Date:

APPENDIX 5: CHILD ASSENT FORM

UEL
University of
East London

Assent Form

Assent to participate in an Experimental Programme Involving the Use of Human Participants

"The Effects of Walking on the Legs, Muscles and Feet of Children"

Name of Researcher: Stephen Cousins

	✓ = YES	✗ = NO
1. I have read the information sheet and been given a copy to keep.		
2. The research project has been explained to me and I know what the research is looking at.		
3. I understand what I have to do.		
4. I understand no one will know I am in the study and that my results are kept a secret.		
5. I understand that only the people doing the work will be able to see my information.		
6. I have been told what will happen to my information when I have finished.		
7. I understand I can stop at any time I want.		
8. I understand I do not have to give a reason for stopping.		

Name: **Signature:** **Date:**

Name of Researcher: **Signature:** **Date:**

APPENDIX 6: SUMMARY OF WITHIN- AND BETWEEN-SESSION RELIABILITY

Table A4.13 Summary of between-session reliability for maximum and minimum transverse plane joint moments during the gait cycle in typically developing children

Table A4.1. Summary of within- (Intraclass Correlation Coefficients, IC: 3,1 and Coefficients of Variation, CoV) and between-session (Mean Difference, ICC: 3,3 and CoV) reliability of *anthropometrical data* in typically developing children aged 7-11 years (N = 45)

	Mean of three trials						
	Within-session measures		**Between-session measures**				
Variable	**ICC (95% CI)**	**CoV (%)**	**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Height (cm)	0.98 (0.94-0.99)	3.84	142.42 ± 7.26	142.35 ± 7.30	0.18 ± 0.15	0.99 (0.93-0.99)	5.01
Body Mass (kg)	0.99 (0.95-0.99)	0.70	36.45 ± 0.28	37.88 ± 0.20	-0.21 ± 0.27	0.99 (0.96-0.99)	0.59
Triceps Skinfold (mm)	0.95 (0.91-0.99)	2.75	10.89 ± 0.30	10.78 ± 0.25	0.29 ± 0.22	0.96 (0.82-0.98)	2.53
Calf Skinfold (mm)	0.90 (0.82-0.96)	11.86	8.25 ± 0.56	8.34 ± 0.49	-0.33 ± 0.42	0.99 (0.92-0.99)	8.38

Table A4.2. Summary of within-session reliability (ICC: 3,1 and CoV) for *peak pressure, peak force, pressure-time integrals and force-time integrals* during barefoot level walking in typically developing children aged 7-11 years (N = 45)

	Mean of three trials							
Region	**Peak pressure (kPa)**		**Peak force (N)**		**Pressure-time integral (kPa/sec)**		**Force-time integral (N/sec)**	
	ICC (95% CI)	**CoV (%)**	**ICC (95% CI)**	**CoV (%)**	**ICC (95% CI)**	**CoV (%)**	**ICC (95% CI)**	**CoV (%)**
Lateral heel	0.90 (0.82-0.96)	10.22	0.88 (0.77-0.95)	13.44	0.91 (0.86-0.97)	14.62	0.81 (0.61-0.86)	17.33
Medial heel	0.83 (0.68-0.90)	12.55	0.90 (0.83-0.94)	12.74	0.88 (0.69-0.92)	13.87	0.88 (0.69-0.93)	17.01
Midfoot	0.85 (0.70-0.92)	15.97	0.71 (0.59-0.82)	17.92	0.83 (0.75-0.86)	19.33	0.76 (0.43-0.80)	18.80
1MTPJ	0.73 (0.60-0.89)	12.88	0.82 (0.67-0.92)	19.21	0.85 (0.79-0.88)	15.61	0.81 (0.62-0.86)	15.47
2-5MTPJ	0.92 (0.84-0.95)	12.52	0.93 (0.82-0.95)	10.95	0.74 (0.51-0.87)	19.84	0.92 (0.75-0.98)	13.37
Hallux	0.74 (0.56-0.88)	13.85	0.71 (0.50-0.86)	18.66	0.69 (0.45-0.84)	17.11	0.69 (0.43-0.73)	17.96
TOES	0.50 (0.29-0.67)	27.15	0.47 (0.18-0.62)	41.67	0.46 (0.15-0.61)	48.31	0.17 (0.03-0.23)	56.08

Table A4.3. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for *peak pressure, peak force, pressure-time integrals and force-time integrals* during barefoot level walking in typically developing children aged 7-11 years (N = 45)

		Mean of three trials				
Variable	**Region**	**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Peak pressure (kPa)	Lateral heel	268.21 ± 54.78	267.68 ± 41.50	2.04 ± 21.20	0.96 (0.92-0.98)	6.81
	Medial heel	228.08 ± 60.65	225.91 ± 58.15	5.65 ± 20.55	0.97 (0.93-0.99)	10.68
	Midfoot	102.75 ± 71.17	99.22 ± 71.35	3.80 ± 21.25	0.99 (0.96-0.99)	16.41
	1MTPJ	149.17 ± 43.97	147.52 ± 47.38	4.61 ± 22.37	0.97 (0.89-0.99)	15.24
	2-5MTPJ	202.25 ± 66.74	203.37 ± 61.41	-6.17 ± 29.83	0.93 (0.79-0.95)	8.50
	Hallux	194.28 ± 63.38	188.39 ± 57.94	3.11 ± 31.72	0.93 (0.83-0.96)	11.26
	TOES	58.32 ± 26.30	88.06 ± 67.83*	11.30 ± 18.79	0.67 (0.48-0.87)	29.64
Peak Force (N)	Lateral heel	754.36 ± 154.25	746.81 ± 133.62	3.51 ± 2.53	0.96 (0.92-0.99)	22.83
	Medial heel	621.98 ± 149.51	624.71 ± 152.33	-5.39 ± 5.78	0.98 (0.94-0.99)	24.78
	Midfoot	305.96 ± 193.37	308.33 ± 226.65	-5.32 ± 5.52	0.79 (0.58-0.84)	26.86
	1MTPJ	411.56 ± 108.78	416.07 ± 107.05	-5.63 ± 3.13	0.95 (0.91-0.99)	23.45
	2-5MTPJ	602.79 ± 182.58	601.25 ± 170.36	5.73 ± 7.94	0.87 (0.67-0.96)	23.38
	Hallux	549.81 ± 158.01	582.27 ± 142.47	-4.42 ± 8.20	0.83 (0.61-0.91)	25.99
	TOES	130.12 ± 69.12	128.44 ± 71.45*	2.97 ± 2.51	0.62 (0.23-0.73)	51.82
Pressure-time integral (kPa/sec)	Lateral heel	28.84 ± 2.94	31.12 ± 3.96	-2.94 ± 3.13	0.98 (0.91-0.99)	12.67
	Medial heel	27.48 ± 3.25	28.33 ± 4.15	-4.18 ± 3.64	0.87 (0.77-0.95)	11.41
	Midfoot	14.60 ± 2.55	16.45 ± 2.28	-1.86 ± 2.50	0.99 (0.93-0.99)	18.14
	1MTPJ	24.82 ± 3.35	26.08 ± 2.65	-2.10 ± 5.43	0.89 (0.80-0.98)	10.13
	2-5MTPJ	32.67 ± 3.90	31.65 ± 3.41	1.90 ± 5.34	0.93 (0.85-0.98)	11.08
	Hallux	27.25 ± 3.65	28.83 ± 3.18	-1.57 ± 5.68	0.96 (0.88-0.98)	11.50
	TOES	9.04 ± 3.26	10.01 ± 3.09*	-0.97 ± 7.74	0.68 (0.47-0.72)	31.75
Force-time integral (N/sec)	Lateral heel	410.72 ± 110.76	434.63 ± 94.63	5.23 ± 5.04	0.93 (0.89-0.96)	25.04
	Medial heel	247.56 ± 121.41	249.11 ± 104.17	-2.93 ± 3.43	0.93 (0.90-0.96)	26.78
	Midfoot	323.05 ± 164.97	350.56 ± 159.83	4.02 ± 5.42	0.83 (0.63-0.89)	36.23
	1MTPJ	283.09 ± 88.86	289.75 ± 84.02	-3.93 ± 3.57	0.95 (0.82-0.98)	29.54
	2-5MTPJ	437.23 ± 151.63	431.07 ± 98.26	5.14 ± 9.09	0.82 (0.63-0.86)	23.71
	Hallux	200.55 ± 44.23	208.33 ± 39.04	3.29 ± 2.68	0.90 (0.85-0.94)	21.85
	TOES	45.23 ± 25.01	58.21 ± 11.13*	5.67 ± 1.99	0.58 (0.25-0.69)	56.61

* denotes a significant difference between session 1 and 2 ($p<0.05$)

Table A4.4. Summary of within- (ICC: 3,1 and CoV) and between-session (Mean Difference, ICC: 3,3 and CoV) reliability for *temporal-spatial parameters* during the gait cycle of level walking in typically developing children aged 7-11 years (N = 12)

	Mean of three trials						
	Within-session measures		**Between-session measures**				
Temporal-spatial parameter	**ICC (95% CI)**	**CoV (%)**	**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Velocity (m/sec)	0.66 (0.35-0.86)	5.48	1.26 ± 0.13	1.36 ± 0.10	-0.14 ± 0.12	0.86 (0.62-0.98)	8.83
Cadence (steps/min)	0.66 (0.47-0.81)	4.86	123.27 ± 10.33	125.73 ± 8.02	-2.83 ± 8.22	0.79 (0.58-0.84)	7.38
Step length (m)	0.86 (0.72-0.93)	4.43	0.62 ± 0.04	0.61 ± 0.03	0.01 ± 0.03	0.93 (0.79-0.95)	5.69
Step width (m)	0.85 (0.70-0.97)	7.82	0.15 ± 0.01	0.18 ± 0.04	-0.02 ± 0.03	0.97 (0.89-0.99)	14.45
Single support (sec)	0.71 (0.60-0.85)	11.67	0.44 ± 0.10	0.43 ± 0.07	0.01 ± 0.02	0.83 (0.75-0.86)	11.49
Double support (sec)	0.64 (0.28-0.92)	12.93	0.17 ± 0.03	0.16 ± 0.01	0.01 ± 0.01	0.87 (0.77-0.95)	11.95

Table A4.5. Summary of within-session reliability (ICC: 3,1 and CoV) for maximum and minimum *sagittal, frontal and transverse plane joint angles* during initial double-support, single-support, terminal double-support and swing phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials					
		Sagittal		Frontal		Transverse	
Maximum and minimum joint angle (^{0})		**ICC (95% CI)**	**CoV (%)**	**ICC (95% CI)**	**CoV (%)**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	0.85 (0.79-0.94)	14.77	0.78 (0.59-0.81)	13.14	0.54 (0.48-0.69)	22.39
	Hip Min	0.81 (0.75-0.91)	12.31	0.78 (0.66-0.87)	16.01	0.64 (0.58-0.69)	29.57
	Knee Max	0.90 (0.77-0.99)	10.07	0.87 (0.80-0.91)	8.32	0.83 (0.71-0.93)	19.28
	Knee Min	0.85 (0.73-0.95)	7.67	0.87 (0.66-0.96)	10.27	0.76 (0.61-0.79)	18.50
	Ankle Max	0.91 (0.83-0.98)	6.27	0.76 (0.51-0.92)	6.65	0.77 (0.63-0.82)	14.87
	Ankle Min	0.85 (0.70-0.99)	4.08	0.73 (0.62-0.90)	6.24	0.63 (0.55-0.68)	13.79
Single-support	Hip Max	0.67 (0.48-0.87)	19.34	0.68 (0.57-0.80)	16.65	0.59 (0.49-0.64)	25.68
	Hip Min	0.79 (0.58-0.84)	16.68	0.63 (0.54-0.70)	21.05	0.57 (0.50-0.66)	22.62
	Knee Max	0.81 (0.73-0.84)	9.28	0.86 (0.73-0.96)	7.20	0.79 (0.68-0.83)	20.09
	Knee Min	0.77 (0.68-0.82)	7.20	0.76 (0.73-0.91)	5.30	0.76 (0.71-0.83)	18.47
	Ankle Max	0.89 (0.82-0.95)	4.41	0.80 (0.68-0.92)	12.00	0.76 (0.70-0.82)	19.61
	Ankle Min	0.83 (0.79-0.91)	3.23	0.75 (0.67-0.82)	6.82	0.87 (0.78-0.95)	18.92
Terminal double-support	Hip Max	0.71 (0.60-0.83)	16.17	0.64 (0.48-0.71)	16.24	0.69 (0.58-0.74)	36.69
	Hip Min	0.74 (0.60-0.85)	14.28	0.57 (0.37-0.61)	23.92	0.54 (0.49-0.59)	24.24
	Knee Max	0.91 (0.83-0.98)	8.08	0.79 (0.66-0.91)	11.59	0.67 (0.61-0.76)	11.43
	Knee Min	0.88 (0.86-0.93)	9.12	0.76 (0.70-0.94)	6.60	0.71 (0.69-0.82)	10.11
	Ankle Max	0.88 (0.77-0.92)	5.51	0.80 (0.76-0.83)	7.53	0.67 (0.56-0.77)	15.02
	Ankle Min	0.84 (0.76-0.91)	5.22	0.88 (0.76-0.93)	8.97	0.79 (0.67-0.85)	15.58
Swing	Hip Max	0.63 (0.51-0.73)	12.93	0.60 (0.56-0.70)	21.87	0.49 (0.34-0.57)	25.72
	Hip Min	0.58 (0.38-0.67)	16.61	0.69 (0.59-0.70)	19.27	0.37 (0.24-0.56)	27.16
	Knee Max	0.78 (0.57-0.72)	9.81	0.87 (0.68-0.94)	13.07	0.58 (0.44-0.69)	16.78
	Knee Min	0.90 (0.79-0.96)	6.42	0.84 (0.79-0.96)	12.93	0.56 (0.49-0.63)	22.38
	Ankle Max	0.76 (0.74-0.87)	7.22	0.83 (0.79-0.86)	15.57	0.54 (0.51-0.73)	21.32
	Ankle Min	0.79 (0.63-0.86)	6.23	0.77 (0.64-0.81)	11.85	0.68 (0.54-0.83)	15.08

Table A4.6. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *sagittal plane joint angles* during initial double-support, single-support, terminal double-support and swing phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint angle (^{0})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	29.29 ± 9.18	26.11 ± 6.91	2.50 ± 3.46	0.66 (0.57-0.72)	25.66
	Hip Min	25.47 ± 1.53	22.04 ± 1.87	2.98 ± 4.48	0.56 (0.47-0.59)	20.17
	Knee Max	15.62 ± 7.28	14.22 ± 8.08	3.23 ± 2.26	0.83 (0.73-0.97)	10.05
	Knee Min	9.55 ± 7.62	8.79 ± 4.49	1.23 ± 1.78	0.82 (0.71-0.96)	14.94
	Ankle Max	7.83 ± 3.91	7.42 ± 2.63	2.43 ± 2.35	0.93 (0.86-0.95)	11.42
	Ankle Min	-1.96 ± 3.74	-2.09 ± 2.15	0.84 ± 2.16	0.98 (0.97-0.99)	10.18
Single-support	Hip Max	26.24 ± 5.02	23.40 ± 4.14	3.73 ± 3.98	0.61 (0.55-0.68)	30.27
	Hip Min	-7.00 ± 3.47	-6.72 ± 4.20	-3.08 ± 3.64	0.73 (0.61-0.78)	27.12
	Knee Max	27.55 ± 8.59	25.17± 7.77	2.62 ± 3.50	0.76 (0.71-0.80)	8.39
	Knee Min	2.62 ± 2.33	3.11 ± 1.50	-1.28 ± 2.73	0.79 (0.75-0.83)	9.82
	Ankle Max	14.18 ± 5.21	14.26 ± 4.65	-3.64 ± 3.36	0.83 0.71-0.84)	18.12
	Ankle Min	-4.12 ± 4.37	-0.27 ± 5.03	-2.27 ± 3.28	0.85 (0.73-0.89)	13.07
Terminal double-support	Hip Max	-2.85 ± 2.95	-3.18 ± 4.95	2.90 ± 2.57	0.58 (0.47-0.62)	25.14
	Hip Min	-7.13 ± -4.54	-7.29 ± -2.90	2.78 ± 3.68	0.49 (0.39-0.52)	22.10
	Knee Max	37.71 ± 1.63	38.90 ± 1.24	-3.61 ± 4.28	0.66 (0.63-0.76)	17.35
	Knee Min	19.14 ± 4.85	17.49 ± 6.35	2.62 ± 4.63	0.77 (0.69-0.83)	14.86
	Ankle Max	12.76 ± 4.65	13.03 ± 5.36	-1.73 ± 3.09	0.97 (0.88-0.99)	12.92
	Ankle Min	-10.57 ± 3.93	-8.26 ± 4.82	-2.05 ± 5.01	0.89 (0.79-0.98)	17.59
Swing	Hip Max	35.30 ± 6.13	34.76 ± 6.05	1.49 ± 3.75	0.24 (0.18-0.39)	26.30
	Hip Min	-5.81 ± 1.90	-4.49 ± 1.87	-2.28 ± 6.04	0.58 (0.45-0.64)	23.33
	Knee Max	46.60 ± 11.96	44.00 ± 12.83	3.38 ± 4.91	0.85 (0.76-0.92)	14.16
	Knee Min	6.54 ± 2.35	6.16 ± 2.92	1.41 ± 1.82	0.96 (0.88-0.99)	16.04
	Ankle Max	7.65 ± 4.54	8.39 ± 4.40	-1.23 ± 3.40	0.87 (0.83-0.98)	25.22
	Ankle Min	-15.36 ± -4.37	-14.48 ± -5.58	-1.70 ± 3.23	0.58 (0.49-0.67)	22.09

Table A4.7. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *frontal plane joint angles* during the initial double-support, single-support, terminal double-support and swing phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint angle (^{0})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	6.34 ± 2.08	3.93 ± 2.02	3.17 ± 3.73	0.69 (0.54-0.78)	22.85
	Hip Min	-0.42 ± 1.20	-0.55 ± 1.33	0.90 ± 1.94	0.88 (0.71-0.93)	27.35
	Knee Max	0.66 ± 1.63	0.69 ± 1.82	-0.79 ± 2.93	0.71 (0.68-0.85)	15.14
	Knee Min	0.51 ± 2.58	0.30 ± 0.90	0.68 ± 2.11	0.98 (0.93-0.99)	17.64
	Ankle Max	3.72 ± 2.77	4.29 ± 1.06	-1.38 ± 2.06	0.96 (0.90-0.99)	14.19
	Ankle Min	0.88 ± 2.06	0.22 ± 1.16	1.29 ± 2.14	0.63 (0.54-0.71)	16.97
Single-support	Hip Max	8.43 ± 3.32	10.07 ± 2.70	-1.74 ± 3.12	0.95 (0.91-0.98)	21.16
	Hip Min	1.64 ± 1.55	1.23 ± 1.67	0.53 ± 1.65	0.92 (0.89-0.95)	23.03
	Knee Max	1.16 ± 1.04	1.52 ± 2.31	-0.83 ± 2.26	0.93 (0.88-0.96)	14.99
	Knee Min	-0.16 ± 1.63	-0.30 ± 1.09	1.06 ± 2.83	0.85 (0.76-0.89)	12.08
	Ankle Max	5.87 ± 2.55	4.90 ± 2.52	1.42 ± 1.52	0.76 (0.70-0.81)	15.40
	Ankle Min	-2.03 ± 1.78	-3.39 ± 3.55	1.60 ± 2.27	0.87 (0.81-0.89)	10.67
Terminal double-support	Hip Max	1.42 ± 2.12	2.55 ± 3.13	-1.85 ± 2.71	0.93 (0.88-0.95)	23.87
	Hip Min	-2.49 ± 4.50	-1.43 ± 3.94	-1.20 ± 2.42	0.92 (0.89-0.96)	15.90
	Knee Max	7.10 ± 5.78	6.37 ± 6.76	1.59 ± 3.98	0.93 (0.88-0.96)	17.41
	Knee Min	-0.14 ± 0.60	-0.27 ± 1.09	1.62 ± 2.14	0.78 (0.73-0.86)	24.91
	Ankle Max	2.07 ± 2.28	1.22 ± 1.72	2.92 ± 2.88	0.91 (0.83-0.94)	9.62
	Ankle Min	0.41 ± 1.59	0.14 ± 2.33	0.45 ± 3.37	0.94 (0.91-0.98)	14.98
Swing	Hip Max	-0.47 ± 1.12	-0.62 ± 2.83	1.17 ± 1.71	0.85 (0.70-0.90)	20.04
	Hip Min	-6.34 ± 2.08	-7.43 ± 4.32	1.22 ± 1.89	0.76 (0.73-0.85)	21.97
	Knee Max	17.32 ± 3.90	11.80 ± 3.94	2.45 ± 4.36	0.82 (0.76-0.85)	18.87
	Knee Min	-3.36 ± 1.70	-3.10 ± 3.96	-0.41 ± 3.52	0.86 (0.73-0.88)	18.47
	Ankle Max	6.71 ± 0.58	5.2 ± 0.99	1.92 ± 3.77	0.61 (0.57-0.66)	23.19
	Ankle Min	-0.07 ± 1.66	-0.11 ± 2.03	0.88 ± 2.85	0.56 (0.45-0.62)	14.19

Table A4.8. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *transverse plane joint angles* during initial double-support, single-support, terminal double-support and swing phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint angle (^{0})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	6.94 ± 4.69	5.37 ± 3.99	1.46 ± 4.68	0.59 (0.57-0.63)	25.11
	Hip Min	-7.89 ± 5.05	-4.04 ± 4.47	-3.72 ± 6.99	0.57 (0.49-0.61)	29.04
	Knee Max	2.70 ± 1.16	1.14 ± 1.63	2.51 ± 3.03	0.34 (0.28-0.37)	24.78
	Knee Min	-7.71 ± 9.07	-8.64 ± 4.35	2.02 ± 4.53	0.41 (0.32-0.47)	29.78
	Ankle Max	1.36 ± 2.32	2.20 ± 1.01	-1.03 ± 2.59	0.37 (0.33-0.40)	24.32
	Ankle Min	-13.71 ± 5.10	-14.83 ± 5.76	1.58 ± 5.09	0.49 (0.38-0.51)	23.62
Single-support	Hip Max	8.43 ± 3.32	9.07 ± 2.76	-1.33 ± 4.72	0.33 (0.26-0.49)	32.56
	Hip Min	-2.20 ± 4.40	-1.46 ± 3.80	-3.02 ± 4.42	0.56 (0.44-0.61)	24.05
	Knee Max	3.97 ± 1.73	4.64 ± 2.13	-1.53 ± 2.87	0.66 (0.59-0.70)	29.33
	Knee Min	-7.83 ± 3.97	-10.03 ± 9.16	1.58 ± 4.83	0.71 (0.62-0.75)	14.27
	Ankle Max	2.36 ± 2.32	3.71 ± 3.03	-1.59 ± 3.02	0.74 (0.71-0.85)	18.87
	Ankle Min	-19.61 ± 4.67	-15.05 ± 8.74	-4.25 ± 4.84	0.73 (0.64-0.79)	26.31
Terminal double-support	Hip Max	10.43 ± 8.32	10.07 ± 2.70	2.57 ± 4.59	0.41 (0.32-0.49)	21.29
	Hip Min	5.69 ± 4.83	2.46 ± 3.03	4.30 ± 6.01	0.48 (0.38-0.54)	30.27
	Knee Max	-1.16 ± 4.98	2.52 ± 2.31	-3.52 ± 5.66	0.49 (0.34-0.55)	26.98
	Knee Min	-2.71 ± 1.33	-3.97 ± 1.71	2.31 ± 5.52	0.53 (0.37-0.59)	24.92
	Ankle Max	-0.28 ± 1.99	-0.17 ± 3.84	-2.37 ± 5.18	0.58 (0.55-0.63)	23.69
	Ankle Min	-8.26 ± 6.78	-8.74 ± 5.03	1.88 ± 6.75	0.61 (0.56-0.67)	22.32
Swing	Hip Max	16.71 ± 5.39	18.53 ± 9.82	-3.09 ± 5.87	0.67 (0.61-0.74)	23.05
	Hip Min	-10.55 ± 8.43	-12.35 ± 3.20	1.60 ± 5.05	0.64 (0.57-0.71)	25.33
	Knee Max	6.65 ± 5.41	5.23 ± 6.52	1.15 ± 4.56	0.58 (0.41-0.62)	29.75
	Knee Min	-12.43 ± 7.90	-11.51 ± 5.20	-2.52 ± 5.26	0.49 (0.37-0.54)	19.67
	Ankle Max	5.87 ± 2.55	4.90 ± 2.52	2.35 ± 4.75	0.55 (0.41-0.59)	29.31
	Ankle Min	-25.89 ± 8.54	-24.24 ± 9.28	-1.13 ± 4.57	0.56 (0.49-0.58)	20.03

Table A4.9. Summary of within- (ICC: 3,1 and CoV) and between-session (Mean Difference, ICC: 3,3 and CoV) reliability for maximum *vertical ground reaction forces* during initial double-support, single-support and terminal double-support phases of level walking in typically developing children aged 7-11 years (N = 12)

	Mean of three trials						
	Within-session measures		**Between-session measures**				
Vertical Ground Reaction Forces (N)	**ICC (95% CI)**	**CoV (%)**	**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	0.97 (0.96-0.99)	4.16	101.11 ± 11.07	107.41 ± 17.50	-7.72 ± 6.43	0.93 (0.90-0.95)	4.84
Single-support	0.95 (0.91-0.99)	6.73	110.23 ± 16.83	113.25 ± 18.57	-6.94 ± 6.77	0.88 (0.82-0.91)	7.26
Terminal double support	0.99 (0.94-0.99)	5.40	96.71 ± 11.31	101.55 ± 9.42	-7.91 ± 9.83	0.91 (0.87-0.96)	6.53

Table A4.10. Summary of within-session reliability (ICC: 3,1 and CoV) for maximum and minimum *sagittal, frontal and transverse plane joint moments* during initial double-support, single-support and terminal double-support phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials					
		Sagittal		Frontal		Transverse	
Maximum and minimum joint moments (Nm/kg^{-1})		ICC (95% CI)	CoV (%)	ICC (95% CI)	CoV (%)	ICC (95% CI)	CoV (%)
Initial double-support	Hip Max	0.92 (0.83-0.95)	5.39	0.96 (0.93-0.99)	11.04	0.76 (0.72-0.81)	6.02
	Hip Min	0.95 (0.91-0.98)	3.94	0.91 (0.84-0.95)	4.26	0.83 (0.79-0.88)	14.68
	Knee Max	0.80 (0.76-0.82)	4.71	0.98 (0.95-0.99)	6.24	0.79 (0.75-0.81)	10.04
	Knee Min	0.86 (0.80-0.90)	9.08	0.98 (0.94-0.99)	7.07	0.97 (0.95-0.99)	14.13
	Ankle Max	0.95 (0.87-0.97)	8.16	0.85 (0.73-0.91)	9.23	0.97 (0.92-0.99)	9.20
	Ankle Min	0.94 (0.90-0.97)	6.05	0.80 (0.76-0.87)	6.79	0.82 (0.77-0.85)	5.93
Single-support	Hip Max	0.95 (0.91-0.98)	10.02	0.94 (0.90-0.97)	4.18	0.77 (0.66-0.81)	11.86
	Hip Min	0.91 (0.87-0.93)	2.63	0.88 (0.83-0.91)	10.92	0.83 (0.73-0.88)	10.94
	Knee Max	0.93 (0.90-0.95)	7.12	0.91 (0.88-0.95)	8.96	0.73 (0.62-0.80)	9.21
	Knee Min	0.90 (0.82-0.93)	8.01	0.86 (0.82-0.90)	12.73	0.82 (0.75-0.85)	12.88
	Ankle Max	0.93 (0.88-0.95)	10.35	0.88 (0.82-0.92)	4.78	0.78 (0.75-0.80)	8.82
	Ankle Min	0.86 (0.80-0.91)	10.04	0.81 (0.77-0.85)	10.85	0.78 (0.71-0.82)	9.07
Terminal double-support	Hip Max	0.96 (0.90-0.99)	3.73	0.92 (0.89-0.95)	8.71	0.87 (0.80-0.90)	11.99
	Hip Min	0.91 (0.84-0.93)	2.20	0.90 (0.87-0.94)	9.56	0.91 (0.84-0.95)	9.85
	Knee Max	0.92 (0.82-0.95)	3.35	0.84 (0.79-0.86)	9.42	0.87 (0.84-0.90)	13.03
	Knee Min	0.83 (0.80-0.89)	5.55	0.75 (0.70-0.78)	8.81	0.81 (0.76-0.84)	6.73
	Ankle Max	0.86 (0.79-0.90)	8.29	0.95 (0.91-0.99)	7.48	0.86 (0.84-0.95)	12.14
	Ankle Min	0.81 (0.77-0.85)	10.27	0.87 (0.82-0.91)	7.91	0.75 (0.70-0.79)	13.47

Table A4.11. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *sagittal plane joint moments* during initial double-support, single-support and terminal double-support phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint moments (Nm/kg^{-1})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	1.12 ± 0.26	1.16 ± 0.71	-0.14 ± 0.16	0.83 (0.80-0.88)	8.13
	Hip Min	0.49 ± 0.15	0.38 ± 0.12	0.11 ± 0.24	0.82 (0.76-0.84)	4.53
	Knee Max	0.20 ± 0.14	0.12 ± 0.08	0.07 ± 0.14	0.78 (0.71-0.80)	12.31
	Knee Min	-0.31 ± 0.11	-0.36 ± 0.18	0.06 ± 0.14	0.86 (0.82-0.91)	13.27
	Ankle Max	0.08 ± 0.03	0.06 ± 0.02	0.06 ± 0.13	0.91 (0.89-0.95)	8.95
	Ankle Min	-0.17 ± 0.13	-0.08 ± 0.07	-0.10 ± 0.05	0.93 (0.90-0.98)	7.52
Single-support	Hip Max	0.74 ± 0.17	0.98 ± 0.24	-0.17 ± 0.20	0.95 (0.93-0.98)	10.70
	Hip Min	-0.80 ± 0.28	-0.65 ± 0.23	-0.23 ± 0.30	0.87 (0.81-0.90)	5.44
	Knee Max	0.34 ± 0.23	0.39 ± 0.28	-0.18 ± 0.24	0.86 (0.82-0.89)	7.53
	Knee Min	-0.10 ± 0.04	-0.14 ± 0.09	0.07 ± 0.17	0.91 (0.88-0.94)	13.71
	Ankle Max	1.18 ± 0.30	1.29 ± 0.44	-0.10 ± 0.14	0.94 (0.85-0.97)	13.13
	Ankle Min	0.26 ± 0.12	0.36 ± 0.19	-0.07 ± 0.15	0.94 (0.91-0.99)	10.86
Terminal double-support	Hip Max	-0.36 ± 0.21	-0.28 ± 0.18	-0.12 ± 0.11	0.86 (0.79-0.90)	10.05
	Hip Min	-0.67 ± 0.24	-0.78 ± 0.35	0.22 ± 0.35	0.81 (0.77-0.86)	8.99
	Knee Max	0.09 ± 0.03	0.11 ± 0.05	-0.07 ± 0.16	0.93 (0.89-0.98)	11.25
	Knee Min	0.04 ± 0.05	-0.01 ± 0.02	0.05 ± 0.14	0.91 (0.83-0.94)	6.21
	Ankle Max	0.95 ± 0.10	0.93 ± 0.19	0.09 ± 0.29	0.91 (0.86-0.96)	7.02
	Ankle Min	0.11 ± 0.05	0.03 ± 0.04	0.04 ± 0.07	0.88 (0.80-0.91)	9.23

Table A4.12. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *frontal plane joint moments* during initial double-support, single-support and terminal double-support phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint moments (Nm/kg^{-1})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	0.42 ± 0.12	0.47 ± 0.19	-0.06 ± 0.17	0.89 (0.80-0.93)	9.26
	Hip Min	-0.12 ± 0.02	-0.09 ± 0.03	-0.09 ± 0.28	0.84 (0.79-0.88)	13.84
	Knee Max	0.22 ± 0.15	0.30 ± 0.14	-0.11 ± 0.13	0.87 (0.85-0.90)	9.11
	Knee Min	0.03 ± 0.03	-0.07 ± 0.06	0.06 ± 0.10	0.82 (0.77-0.86)	7.67
	Ankle Max	0.08 ± 0.03	0.06 ± 0.02	0.03 ± 0.11	0.89 (0.86-0.94)	8.95
	Ankle Min	0.03 ± 0.02	0.02 ± 0.04	0.03 ± 0.06	0.88 (0.79-0.90)	7.23
Single-support	Hip Max	0.55 ± 0.13	0.54 ± 0.19	0.04 ± 0.13	0.81 (0.77-0.85)	9.99
	Hip Min	0.07 ± 0.10	0.04 ± 0.07	0.07 ± 0.21	0.77 (0.69-0.80)	13.87
	Knee Max	0.30 ± 0.17	0.37 ± 0.09	-0.12 ± 0.21	0.90 (0.88-0.94)	11.10
	Knee Min	-0.07 ± 0.14	-0.03 ± 0.13	-0.08 ± 0.11	0.81 (0.79-0.85)	13.08
	Ankle Max	0.21 ± 0.13	0.18 ± 0.06	0.09 ± 0.17	0.90 (0.83-0.92)	12.61
	Ankle Min	0.07 ± 0.02	0.04 ± 0.05	0.04 ± 0.12	0.94 (0.92-0.98)	10.06
Terminal double-support	Hip Max	0.24 ± 0.17	0.27 ± 0.10	-0.08 ± 0.22	0.85 (0.81-0.90)	6.24
	Hip Min	-0.15 ± 0.07	-0.14 ± 0.04	-0.09 ± 0.21	0.90 (0.83-0.92)	4.68
	Knee Max	0.09 ± 0.03	0.06 ± 0.04	0.06 ± 0.15	0.83 (0.77-0.86)	10.41
	Knee Min	-0.20 ± 0.08	-0.14 ± 0.07	-0.04 ± 0.07	0.81 (0.78-0.86)	13.92
	Ankle Max	0.12 ± 0.03	0.14 ± 0.05	-0.03 ± 0.16	0.96 (0.94-0.99)	11.08
	Ankle Min	-0.01 ± 0.06	-0.04 ± 0.05	0.07 ± 0.15	0.97 (0.95-0.99)	10.72

Table A4.13. Summary of between-session reliability (Mean Difference, ICC: 3,3 and CoV) for maximum and minimum *transverse plane joint moments* during initial double-support, single-support and terminal double-support phases of level walking in typically developing children aged 7-11 years (N = 12)

		Mean of three trials				
Maximum and minimum joint moments (Nm/kg^{-1})		**Session 1 (Mean ± SD)**	**Session 2 (Mean ± SD)**	**Mean Difference**	**ICC (95% CI)**	**CoV (%)**
Initial double-support	Hip Max	0.07 ± 0.14	0.03 ± 0.13	0.07 ± 0.04	0.74 (0.70-0.76)	14.87
	Hip Min	-0.09 ± 0.03	-0.08 ± 0.06	-0.03 ± 0.04	0.67 (0.61-0.70)	13.74
	Knee Max	0.05 ± 0.09	0.04 ± 0.07	0.04 ± 0.03	0.76 (0.73-0.80)	8.71
	Knee Min	-0.01 ± 0.08	0.00 ± 0.09	-0.02 ± 0.04	0.78 (0.75-0.83)	11.61
	Ankle Max	0.03 ± 0.06	0.01 ± 0.01	0.04 ± 0.02	0.66 (0.62-0.69)	7.05
	Ankle Min	-0.02 ± 0.03	0.00 ± 0.03	-0.03 ± 0.06	0.71 (0.68-0.74)	9.93
Single-support	Hip Max	0.17 ± 0.06	0.19 ± 0.13	-0.04 ± 0.04	0.59 (0.50-0.66)	16.78
	Hip Min	-0.12 ± 0.10	-0.11 ± 0.11	-0.02 ± 0.05	0.57 (0.52-0.60)	12.28
	Knee Max	0.11 ± 0.10	0.17 ± 0.12	-0.04 ± 0.05	0.56 (0.49-0.59)	11.88
	Knee Min	0.01 ± 0.06	0.01 ± 0.11	0.01 ± 0.04	0.67 (0.64-0.72)	17.50
	Ankle Max	0.12 ± 0.08	0.10 ± 0.04	0.02 ± 0.04	0.71 (0.68-0.74)	14.46
	Ankle Min	-0.03 ± 0.06	-0.06 ± 0.08	0.03 ± 0.05	0.62 (0.59-0.67)	11.65
Terminal double-support	Hip Max	0.09 ± 0.03	0.07 ± 0.10	0.04 ± 0.06	0.58 (0.55-0.60)	8.81
	Hip Min	0.01 ± 0.02	0.01 ± 0.06	0.02 ± 0.04	0.73 (0.71-0.78)	16.09
	Knee Max	0.09 ± 0.03	0.11 ± 0.06	-0.04 ± 0.11	0.70 (0.66-0.72)	11.26
	Knee Min	-0.10 ± 0.07	-0.06 ± 0.12	-0.06 ± 0.14	0.78 (0.69-0.80)	9.19
	Ankle Max	0.06 ± 0.02	0.09 ± 0.08	-0.07 ± 0.12	0.60 (0.57-0.66)	10.13
	Ankle Min	-0.07 ± 0.05	-0.09 ± 0.07	0.07 ± 0.19	0.77 (0.72-0.83)	13.09

APPENDIX 7: SUMMARY OF RELATIONSHIPS BETWEEN NORMALISED PEAK FORCE DATA AND THE SIGNIFICANT BETWEEN-GROUP FRONTAL AND TRANSVERSE PLANE KINETIC PARAMETERS

Table A7.1. Relationships between normalised peak force data at the MID and 2-5MTPJ and between-group frontal plane kinetic differences in walking (r indicates the strength and the direction of a relationship between variables)

		Midfoot normalised peak force (r)	2nd-5th metatarsals normalised peak force (r)
Minimum hip moment during SS (frontal)	Obese	-0.34	0.14
	Overweight	-0.33	-0.23
	Combined	-0.38	0.08
Maximum knee moment during SS (frontal)	Obese	0.34	0.39
	Overweight	-0.45	0.21
	Combined	-0.15	0.20

Table A7.2. Relationships between normalised peak force data at the MID and 2-5MTPJ and between-group transverse plane kinetic differences in walking (r indicates the strength and the direction of a relationship between variables)

		Midfoot normalised peak force (r)	2^{nd}-5^{th} metatarsals normalised peak force (r)
Minimum hip moment during IDS (transverse)	Obese	-0.02	-0.10
	Overweight	0.59	-0.39
	Combined	0.23	-0.21
Maximum hip moment during SSS (transverse)	Obese	-0.07	-0.06
	Overweight	-0.20	-0.09
	Combined	-0.07	-0.13
Minimum knee moment during IDS (transverse)	Obese	0.35	-0.01
	Overweight	0.21	0.40
	Combined	0.35	-0.08
Minimum knee moment during TDS (transverse)	Obese	0.07	0.13
	Overweight	0.53	0.21
	Combined	0.03	0.35
Maximum knee moment during IDS (transverse)	Obese	-0.21	-0.28
	Overweight	-0.13	-0.22
	Combined	-0.09	-0.32
Maximum knee moment during SS (transverse)	Obese	0.01	-0.14
	Overweight	-0.38	0.26
	Combined	-0.08	-0.10
Maximum knee moment during TDS (transverse)	Obese	-0.01	-0.03
	Overweight	-0.32	0.26
	Combined	-0.09	-0.01
Minimum ankle moment during IDS (transverse)	Obese	-0.00	0.40
	Overweight	0.18	0.31
	Combined	0.07	0.22
Minimum ankle moment during TDS (transverse)	Obese	-0.13	0.48
	Overweight	0.11	0.08
	Combined	-0.10	0.32
Maximum ankle moment during IDS (transverse)	Obese	-0.46	0.41
	Overweight	-0.17	-0.43
	Combined	-0.17	-0.12
Maximum ankle moment during SS (transverse)	Obese	0.30	-0.31
	Overweight	-0.48	-0.27
	Combined	0.08	0.23
Maximum ankle moment during TDS (transverse)	Obese	0.09	-0.18
	Overweight	0.45	0.21
	Combined	-0.04	-0.24

APPENDIX 8: SUMMARY OF PAPERS AND PRESENTATIONS

Journal Articles:

Cousins, SD; Morrison, SC and Drechsler, WI. (2012). The reliability of plantar pressure assessment during barefoot level walking in children aged 7-11 years. *Journal of Foot and Ankle Research*, 5:8.

Morrison, SC; Mahaffey, RD; Cousins, SD and Drechsler, WI. (2012). Current understanding of the impact of childhood obesity on the foot and lower limb. *Journal of the Association of Paediatric Chartered Physiotherapists*, 3(2), 5-11.

Cousins, SD; Morrison, SC and Drechsler, WI. (2013). Foot loading patterns in normal weight, overweight and obese children aged 7 to 11 years. *Journal of Foot and Ankle Research*, 6:36.

Presentations:

Cousins, S; Morrison, S; Drechsler, W. (2011). The reliability of plantar pressure assessment in children aged 7 to 11 years. 16th Annual Congress of the European College of Sport Science, Liverpool John Moores University, 6th-9th July, Liverpool, UK. Poster Presentation.

Cousins, S; Morrison, S; Drechsler, W. (2011). What are the effects of excessive body mass of foot loading in children? 16th Annual Congress of the European College of Sport Science, Liverpool John Moores University, 6th-9th July, Liverpool, UK. Oral Presentation.

Morrison, S.C., Cousins, S.D., Drechsler, W.I. (2011) Plantar Pressure Characteristics in Obese Children. Annual Conference of the Society of Chiropodists and Podiatrists. Oral Presentation

Cousins, S; Morrison, S; Drechsler, W. (2012). Cluster Analysis to Classify Foot Loading Patterns in Obese, Overweight and Normal Weight Children. 5th Exercise and Sport Science Australia Conference, 19th-21st April, Gold Coast, Queensland, AUS. Oral Presentation.

Morrison, S.C., Cousins, S.D., Drechsler, W. (2013) Foot loading is altered in overweight and obese children: Findings from plantar pressure analysis. 20th European Congress on Obesity. Poster Presentation.