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Childhood foot structure and function: is this influenced by obesity?

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**Childhood foot structure and function:
Is this influenced by obesity?**

A thesis submitted in fulfilment of the
requirements for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Diane L Riddiford-Harland

BEd, MSc(Hons)

School of Health Sciences

2010

Dedication

I dedicate this thesis to my husband and our two boys.

Declaration

I, Diane L Riddiford-Harland, declare that this thesis “Childhood foot structure and function: Is this influenced by obesity?”, submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged below. This thesis has not been submitted for a degree at any other university or institution.

Diane L Riddiford-Harland

16 December 2010

Publications

This thesis includes chapters that have been written as the following journal articles::

Chapter 2: Riddiford-Harland DL, Steele JR, Baur LA. The use of ultrasound imaging to measure midfoot plantar fat pad thickness in children. *Journal of Orthopedic and Sports Physical Therapy* 2007; 37: 644-647.

Chapter 3: Riddiford-Harland DL, Steele JR, Baur LA. Are the feet of obese children fat or flat: Revisiting the debate. *International Journal of Obesity* 2010; doi:10.1038/ijo.2010.119.

Chapter 4: Riddiford-Harland DL, Steele JR, Baur LA. Fat feet and plantar pressures: Are these related in children? *International Journal of Pediatric Obesity*. Resubmitted for publication 11 November, 2010.

Chapter 5: Riddiford-Harland DL, Steele JR, Baur LA, Cliff DP, Okely AD, Morgan PJ, Jones RA. Physical activity and pressure distribution beneath the feet: Are these factors related in overweight and obese children? *International Journal of Obesity*. Submitted for publication 9 December, 2010 (2010IJO01590).

Chapter 6: Riddiford-Harland DL, Steele JR, Cliff DP, Okely AD, Morgan PJ, Jones RA, Baur LA. Plantar pressure, foot structure and physical activity: Are these factors moderated by a physical activity program in overweight and obese children? *International Journal of Obesity*. Submitted for publication 16 December, 2010 (2010IJO01618).

As the primary supervisor, I, Professor Julie Steele, declare that the greater part of the work in each article listed above is attributed to the candidate, Diane Riddiford-Harland. In each of the above manuscripts, Diane contributed to study design and was primarily responsible for data collection, data analysis and data interpretation. The first draft of each manuscript was written by the candidate and Diane was then responsible for responding to the editing suggestions of her co-authors. The co-authors, Professor Julie Steele (Chapters 1-6) and Professor Louise Baur (Chapters 1-6), were responsible for assisting in study design, interpreting data and editing all the manuscripts. Associate Professor Tony Okely, Associate Professor Philip Morgan, Dr Dylan Cliff and Dr Rachel Jones (Chapters 5-6) were also involved in the design of the HIKCUPS study from which a cohort of participants was recruited. In addition, Rachel Jones was responsible for recruitment of HIKCUPS participants whereas Dylan Cliff was responsible for HIKCUPS physical activity data collection and data analysis. Diane has been solely responsible for submitting each manuscript for publication to the relevant journals, and she has been in charge of responding to reviewer's comments, with assistance from her co-authors.

Diane L Riddiford-Harland
Candidate
16 December 2010

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16 December 2010

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Abstract

Obesity in childhood has been associated with numerous negative health consequences, which can contribute to a reduced quality of life and poor long-term health prognosis. Although compromise to the musculoskeletal system of children as a result of habitually carrying excess adiposity has been reported, it is not clear how obesity affects the developing feet of young children. Identifying possible negative effects of excess body mass on the feet of overweight and obese children could assist in preventing future foot complications and in the design of appropriate interventions to promote healthy outcomes for these children. Therefore, the aim of this thesis was to systematically investigate the effects of overweight and obesity on foot structure and function in school-aged children.

This thesis aim was achieved through a series of studies, the first of which established a reliable protocol to quantify the midfoot structure of young children's feet. Once this protocol was established four studies were conducted to examine structural and functional characteristics of the feet of prepubertal school-aged children (aged between 5 and 9 years) of varying body mass index. Parameters quantified in these studies included height, body mass, external foot dimensions, medial midfoot fat pad thickness, internal arch height, dynamic plantar pressure distributions and physical activity participation.

The combined results of these studies revealed that overweight and obese children's feet are fatter and flatter than those of their non-obese counterparts. The medial midfoot fat padding in these overweight and obese children was thicker than that of non-obese children, although it did not appear to provide any functional protection for the feet of these overweight and obese children during walking. Dynamic plantar pressures generated by these school-aged children were positively associated with body

mass and inversely associated with physical activity intensity. After these children participated in a weight-bearing physical activity intervention, their body mass and plantar pressure distributions were stabilised with no apparent effect of the program on their foot structure and function. Plantar pressures, however, remained high at program completion and the pressure-time integrals significantly increased from pre- to post-intervention.

Based on the results of this thesis it is postulated that the developing feet of overweight and obese children may be at risk of foot pain, discomfort or dysfunction due to the high plantar pressures generated by these children due to their excess body mass. Interventions designed to reduce pressures generated beneath the feet of overweight and obese school-aged children while still encouraging these children to participate in adequate levels of physical activity are warranted.

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Chapter 1

The Problem

Introduction

Numbers of overweight and obese individuals worldwide continue to escalate, with this disease and its associated negative health consequences contributing to a reduction in quality of life and ultimately a decreased life expectancy (1,2). Extensive research has been conducted into preventions, treatments and cures for this epidemic due to the devastating complications experienced by obese adults, including cardiovascular disease, diabetes mellitus, hypertension, cancer, psychological dysfunction and musculoskeletal abnormalities (3). More recently, studies have investigated this disease in the paediatric population to find that obese youngsters present with the same debilitating effects often apparent in obese adults (2-4). Similar to adults, a contributing factor to the perpetuating cycle of obesity is that overweight and obese children tend to be less physically active and display increased sedentary behaviours as compared to their non-overweight peers (5,6). Unfortunately, paediatric obesity often leads to adolescent and adult obesity (2,4,7) with the probability that complications evident during childhood will be exacerbated in later life.

One of the consequences associated with childhood obesity that is likely to affect the ability of children to be physically active is musculoskeletal dysfunction (8,9). Musculoskeletal dysfunction experienced by obese children and adolescents includes reduced lower limb strength (10,11), difficulty performing activities of daily living (9,10,12), increased incidence of bone stress and fracture (9,13), neck and back pain (14,15), slipped capital femoral epiphysis (16,17), hip and knee osteoarthritis/pain

(14,18), tibia vara (19) and ankle and foot pain (14,20,21). Of these complications, less well researched are the effects of childhood obesity on developing foot structure and function.

Appropriate structural development is necessary as the foot is the final link in the lower limb kinetic chain that opposes the effect of ground reaction forces generated during each step (22). The skeletal architecture of the foot forms the basis for the longitudinal (medial and lateral portions) and transverse arches, which the muscular and ligamentous tissues maintain. This arched structure enables the foot to support and balance the body's mass, act as a semi-rigid lever to propel the body during gait and be resilient enough to allow absorption of sudden impact forces. Musculoskeletal tissue dysfunction can result in abnormal foot mechanics, which may in turn lead to pain, injury, or deformity of the leg and/or foot. Excessive weight-bearing in obese adults has been shown to result in altered foot mechanics as evidenced by abnormal foot/ground contact patterns during walking (23-25). Messier et al. (25) and Hills et al. (26) postulated an association between poor foot mechanics in adults and the limited involvement by obese individuals in activities of daily living or exercise regimes. Implications of this postulation include a perpetuation of obesity via limited physical activity induced by foot dysfunction, with a poor prognosis for overweight and obese children (27).

One of the first studies to speculate on the detrimental effects of obesity on foot structure in children was a study of 426 prepubertal children (8). Previously, studies had investigated medial longitudinal arch type, foot shape, footprints and foot growth in infants through to older children and adolescents, but without reference to how these structures were affected by the need to bear excess body mass, particularly during the early developmental period (28-30). To therefore investigate the effects of obesity on

prepubertal foot structure, Riddiford-Harland et al. (8) collected static footprints for 62 obese children and 62 age- and sex-matched non-obese children. The authors derived and examined footprint indices for these children to conclude that excess body mass had a significant effect on the footprints of obese children. That is, the obese children displayed a significantly greater foot-ground contact area than their leaner counterparts (Figure 1; 31). A study by Napolitano et al. (32) also suggested that obesity might have a substantial impact on the lower limbs of children during the period of physiologic ligament laxity, which is normal in young children. Numerous studies utilising external measures, footprints, three-dimensional scans, radiology, photography and computed tomography scans have since maintained the belief that young obese children and adolescents have more robust, flatter feet and, hence, lowered arches when compared to their normal weight peers (33-35).



Figure 1. A sample of weight-bearing footprints recorded with a pedograph for an obese (left) and non-obese prepubertal child aged 8 years (31; p 105).

Beneath the plantar surface skin of the foot are complex shock-dissipating structures of adipose tissue. These structures, termed fat pads, comprise fat globules

encased by fibroelastic septae and are necessarily located at the weight-bearing sites of the foot, such as under the heel and under the metatarsal heads (36,37). Fatty tissue also continues the length of the foot to insulate structures located deeper within the foot. In the newborn foot, in addition to the heel and metatarsal fat pads, Tax (38) identified three common types of fat padding, which he claimed gradually disappeared by 2 to 4 years of age and which posed no risk to normal foot development. The first type was a large fatty pad located in the longitudinal arch area of the foot that may mask the contour of the arch. The second was a marble-sized mass, often positioned beneath the talus or navicular bones with a third fatty pad evident on the dorsum of the foot (38,39). Studies have indicated that children are born with flat feet, which are caused by excess subcutaneous fat on the plantar surface of the foot (40,41). Although not of weight-bearing or propulsive importance at birth, no studies could be located that have investigated either the histological make-up or function of these fat pads or to determine their effect on development once ambulation occurs.

By 6 years of age the tensile strength of the ligamentous, bony and muscular structures of the foot should have increased so that a child's foot loses its immature features and takes on the characteristics of an adult weight-bearing foot (21,38,42). However, it has been questioned whether obese children's feet remain robust and appear flat, as a result of fatty tissue that has not yet disappeared from the medial arch area (43), or whether the medial longitudinal arch is lowered as a result of the need to continually bear excess body mass, which is likely to be associated with foot complications at this early age (8). Further complicating this determination is general prepubertal growth such that lower limb alignment changes in children at this age may influence foot posture and hence arch structure (44).

One of the challenges confronting those studying the structure of children's developing feet is how to best measure them and to then determine the effect paediatric obesity poses to the feet of children. Various methods for assessing longitudinal arch characteristics of the child's foot have been utilised, including clinical assessment, three-dimensional scans, magnetic resonance imaging, radiographs and pedography. Clinical observation, no matter how accurately completed, is limited by subjectivity (45) and the need to be complimented by objective assessment techniques. Magnetic resonance imaging, scans and radiographs, while providing clear visual evidence of foot structure, require expensive and complex equipment, which are located in specialised facilities and are therefore difficult to access for large study cohorts. Radiography is also an inappropriate research tool for assessing the feet of otherwise healthy children due to radiation exposure. Alternatively, pedography is a simple, non-invasive method to permanently record a weight-bearing footprint of children, and is particularly suitable for large cohorts (8,46). Numerous angles and indices have been calculated from footprints in an attempt to define medial longitudinal arch status, particularly vertical arch height (29,47). However, controversy surrounds the use of external foot parameters, or indirect methods of analysis, to assess the internal structure and function of the foot. The literature is therefore still divided on the most appropriate method to measure the feet of children, particularly internal foot structures such as fat pad thickness. Also, whether the structural nature of obese children's feet is compromised as a result of continually carrying excess adiposity, or if their feet are just fat and not structurally compromised, is not known.

Knowledge of overweight and obese children's foot structure is necessary to investigate foot function. Functionally, the heel contacts the ground to provide a base of support during the stance phase of gait. As the body continues forward, the foot

accommodates an individual's body mass while the swing-through phase of the opposite lower limb occurs. The forefoot and toes then propel the body forward to continue the gait cycle. Although young children's feet grow rapidly, development is not complete until approximately 18 years (38). Therefore, detrimental consequences of excessive loading during gait on the still developing foot structures appear likely. It has been postulated that the continual bearing of excess body mass on the feet during activity may lead to foot injury or foot dysfunction in young children (48).

Calculating peak pressure distribution beneath the plantar surface of the feet, as a method of functional foot assessment, has been validated in children and adults (42,49). Functional foot assessment of overweight and obese children during walking has identified these children as displaying higher pressure distributions beneath their feet when compared to their leaner counterparts (27,48,50). Hennig et al. (51) identified body weight as a major influence on the magnitude of the pressures under the feet of 125 children aged 6 to 10 years. Significantly higher peak pressures were reported by David et al. (52) in an obese group of children aged 5 to 11 years when compared to normal-weight children. Obese children also generated significantly greater peak dynamic forefoot pressures when the results of 13 obese and 13 non-obese prepubertal children (8 years of age) were compared (53).

Higher plantar pressure distributions in adults have been associated with potential foot discomfort or injury and a reduction in the amount of physical activity these individuals perform (27). As increased physical activity is one recommended approach to combating the epidemic of obesity among children (1,54), it has been speculated that if overweight and obese children experience potential foot complications due to higher peak pressures, they may be less inclined to participate in physical activity and reluctant to increase their physical activity (28). Therefore, as the feet are the base

of support for the body and the mechanism for propulsion during physical activity, complications as a result of excess adiposity on the developing feet of young children requires systematic investigation.

Statement of the Problem

The primary aim of this thesis was to systematically investigate the effects of overweight and obesity on foot structure and function in school-aged children. To achieve this aim a new and novel imaging method that can directly measure the structural features of a child's midfoot was initially developed (Chapter 2) so that the effects of paediatric obesity on foot structure could be reliably quantified (Chapters 3 and 4). To then investigate the effects of overweight and obesity on foot structure, a relatively large cohort of prepubertal children was investigated using the direct method developed in Chapter 2, to determine the structure of the feet of overweight and obese children (Chapter 3). These structural characteristics of the overweight and obese children's feet and how they related to foot function, characterised by dynamic plantar pressures, was then investigated (Chapter 4). The relationship between overweight and obese children's foot function and the children's participation in physical activity was then systematically investigated (Chapter 5). Whether participation in a weight-bearing physical activity program moderated foot structure and function in overweight and obese children, was then explored (Chapter 6).

To avoid health complications in later life a reduction in overweight and obesity among young children is necessary. One agreed method to achieve this aim is through increased physical activity participation. However, before exercise or physical activity prescription can be determined it is necessary to understand if and how obesity impacts upon the developing feet of children because these structures must efficiently and

comfortably support the body during such dynamic tasks. Establishing how involvement in physical activity by these children impacts on foot development and foot function will assist in the formulation of both coping and intervention strategies to be recommended to parent/guardians, paediatricians and educators of children inflicted with this disease.

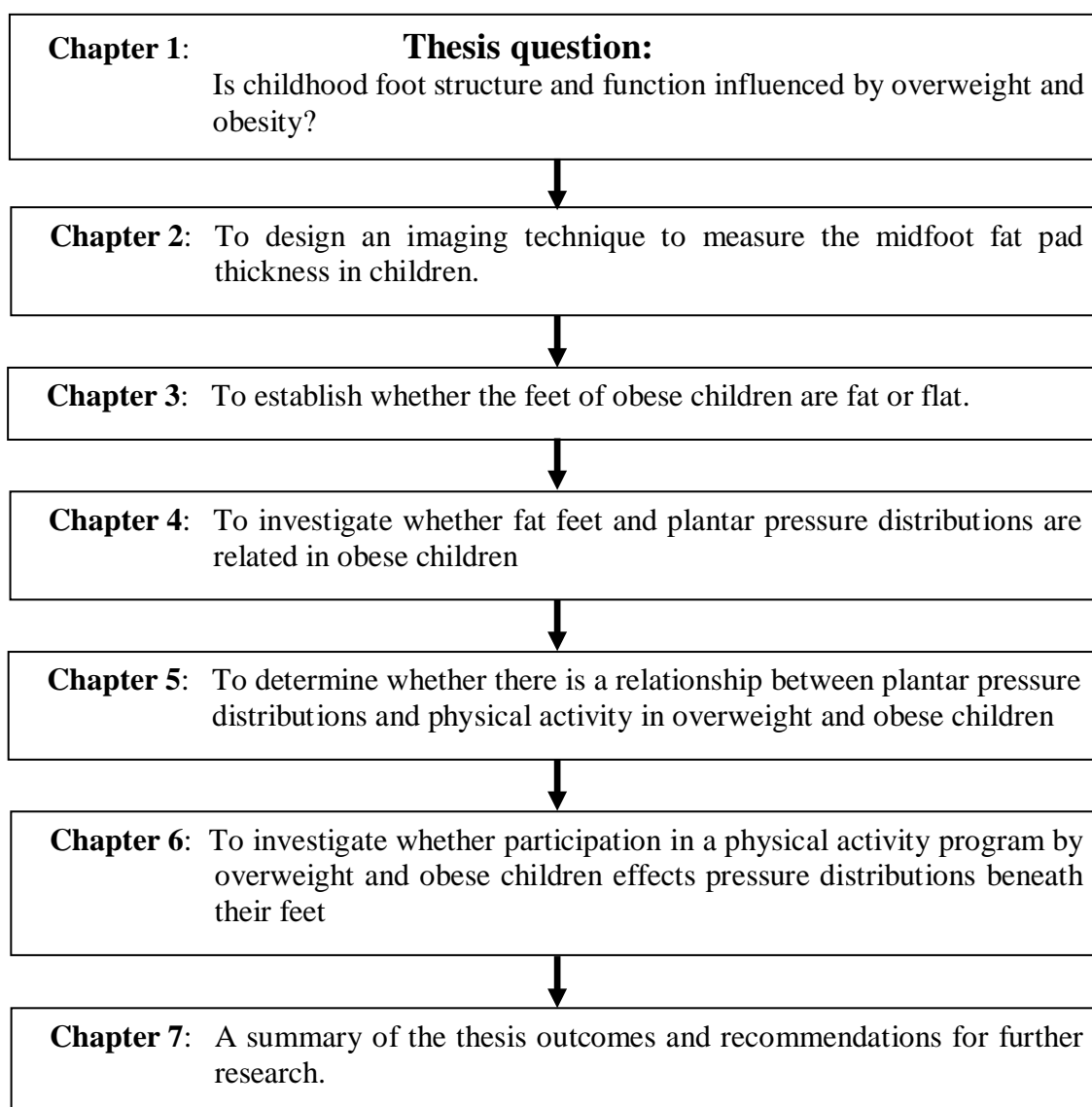


Figure 2. A schematic representation of the thesis structure with the aim of each chapter to systematically investigate foot structure and function in overweight and obese children.

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Chapter 2

The use of ultrasound imaging to measure midfoot plantar fat pad thickness in children

This chapter is an amended version of the manuscript: Riddiford-Harland DL, Steele JR, Baur LA. The use of ultrasound imaging to measure midfoot plantar fat pad thickness in children. *Journal of Orthopaedic and Sports Physical Therapy* 2007; 37: 644-647.

Abstract

Study Design: Descriptive and reliability study.

Objectives: To design a reliable imaging method to quantify the thickness of the medial midfoot plantar fat pad in the feet of young children and to determine any between-foot (right versus left) differences in thickness.

Background: Before we can establish whether persistent fat padding in the medial midfoot or a structural collapse of the longitudinal arch is the mechanism of flatter footprints displayed by obese children, a reliable method to quantify midfoot plantar fat pad thickness in children is required.

Methods and Measures: A portable ultrasound imaging system was used to quantify medial midfoot plantar fat pad thickness for the right and left foot of 14 healthy children (mean \pm SD: 3.8 \pm 0.8 years) using three different measurement techniques. Intraclass correlation coefficients (ICC) and standard error of the measurement (SEM) were calculated to assess intrarater reliability of these measurement techniques.

Results: Medial midfoot plantar fat pad thickness (method 1, right foot) ranged from

3.1 to 4.9 mm. Similar values were observed for methods 2 and 3. The ICC values (0.82 to 0.94) and SEM values (0.12 to 0.23 mm) suggested that all three methods provided good reliability. Based on an ANOVA model, there was no significant interaction and no significant main effect for side, method, or day between the measurement techniques.

Conclusions: We found ultrasonography to be a reliable field tool to quantify medial midfoot plantar fat pad thickness in children. Although there was no difference in reliability across the 3 measurement techniques, the technique in which the transducer was placed directly beneath the dorsal-navicular landmark was the most time-efficient procedure to measure the thickness of the midfoot plantar fat pad in young children.

Introduction

There are developmental changes in the fat padding of the feet during childhood. The presence of a fat pad under the medial aspect of the foot of infants at birth was observed by Tax (1) who noted that this fatty pad disappeared in the immature foot by 4 years of age. Volpon (2) investigated the footprints of children from birth to 15 years and reported that major changes in the medial arch contour and, in turn, resolution of a flat-footed appearance, occurred between the ages of 2 and 6 years. Fat padding in the medial midfoot was also detected by Hefti and Brunner (3) who suggested that the fat padding might remain in the midfoot until closer to the age of 6 years.

Obese prepubertal children display a broader, flatter footprint, particularly in the midfoot, than their non-obese counterparts (4-6). It is possible that these broader footprints, characteristic of obese children's feet, indicate that fat padding in the medial midfoot persists in these children after the age of 6 years to protect the developing foot structures from higher loading associated with increased body mass (5). Alternatively,

the flatter footprints displayed by obese children may reflect a collapse of the medial longitudinal arch due to excessive loading of the feet caused by the children continually bearing additional body mass. As proper mechanics of the longitudinal arch are critical to normal foot function (1), it is important to establish whether persistent fat padding in the medial midfoot or a structural collapse of the longitudinal arch is the mechanism of flatter footprints displayed by obese children. However, before such an investigation can be undertaken, a reliable imaging method to quantify midfoot plantar fat pad thickness in children is required. Therefore, the primary aim of this study was to design a reliable imaging method to quantify the thickness of the medial midfoot plantar fat pad in the feet of young children. Ultrasound was chosen as the imaging method due to its noninvasive, nonradiating properties and its portability, which were essential criteria for testing children. Three methods were tested to identify the most reliable and time-efficient option. A secondary aim was to determine whether there was any difference in the medial midfoot fat pad thickness between the children's right and left feet.

Methods

Subjects

Four girls and 10 boys (mean age 3.8 ± 0.8 years, height 1.03 ± 0.08 m, weight 17.4 ± 2.2 kg, body mass index 16.3 ± 1.4 kg/m²) with no history of foot or lower limb pathology were invited to participate in this study. All procedures were approved by the University of Wollongong Human Research Ethics Committee and written, informed consent was obtained from the children's parents prior to testing. All measurements were taken by the one trained observer [DLRH] at each subject's home, in the presence of at least one parent or caregiver.

Procedures

A portable ultrasound system (SonoSite® 180PLUS, Bothell, WA, USA) was used to quantify plantar fat pad thickness in the midfoot region of each child's right and left foot. A 10-5 MHz, 38 mm linear array transducer was selected as the high-frequency transducer provided greater clarity of the superficial fat padding in the middle region of the foot (7). The shallow depth and wide field of view associated with the linear array transducer also enhanced imaging of the structures in this midfoot area (7,8).

Extensive pilot testing established the joint between the inferior aspect of the navicular and middle cuneiform as a landmark in the medial midfoot that could be clearly identified using ultrasound. We aimed to reliably measure the thickness of the plantar fat pad directly beneath this anatomical site. To determine the most reliable and time-efficient method to quantify fat pad thickness values at this site, three methods to locate this site and then measure the fat pad thickness were undertaken. In all three methods, the transducer was placed longitudinally on the plantar surface of the foot while the child sat with their lower extremity flexed at the knee and the foot held in a relaxed position (Figure 1).

For method 1 the transducer was positioned on the plantar surface of the foot directly beneath an external landmark located on the dorsal aspect of the navicular. The joint between the inferior aspect of the navicular and middle cuneiform was then identified and the ultrasound image captured. In contrast, during method 2 and method 3, the ultrasound transducer was moved across the plantar surface of the foot to locate the joint between the inferior aspect of the navicular and middle cuneiform, anterior to posterior in method 2 (by first identifying the second phalanges, metatarsal and tarsal bones) and posterior to anterior in method 3 (by first identifying the calcaneus).



Figure 1. Subject positioning and ultrasound transducer placement to measure medial midfoot fat pad thickness.

The system's calliper function was then used to measure the distance from the most external view of the image to the superior line of the plantar fascia (Figure 2). Two trials per foot were collected on three consecutive days, with no more than four days between any of the testing sessions.

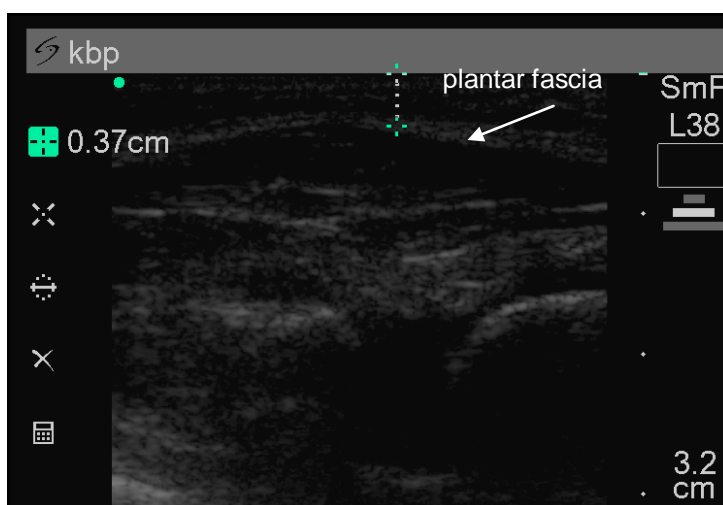


Figure 2. Sonograph of the plantar midfoot indicating the location of the fat pad thickness (0.37 cm).

Statistical Analysis

Means, standard deviations, and ranges were calculated for the midfoot plantar fat pad thickness values obtained for the children's right and left feet, using the three data collection methods over the three test days. To assess intrarater reliability, intraclass correlation coefficients (ICC; 9) and standard error of the measurement (SEM), and smallest real difference (SRD) were calculated. An ICC_{3,1} was used to assess within-day intrarater reliability for each of the three measurement methods. ICC_{3,2}, using mean of the two measurements from each testing day, was used to assess between-day intrarater reliability. The SEM ($\text{pooled SD} \times \sqrt{1-\text{ICC}}$; 10) was calculated to assess response stability across the three measurement techniques and across the three measurement sessions. To determine the minimum change in measurement that could be interpreted as a true difference, the smallest real difference (SRD) was calculated using the formula: $\text{SRD} = \text{SEM} \times \sqrt{2} \times \bar{x} \times 2.16$ (where 2.16 = 95% CI for t distribution with 13 df ; 10).

A repeated measures analysis of variance (ANOVA) design with 3 factors; side (right and left), method (1, 2, and 3) and day (1, 2, and 3) was then used to determine whether there were any significant ($p < 0.05$) differences between the feet of the children, among methods and among days.

Results

Midfoot plantar fat pad thickness data obtained for the right and left foot of the 14 children are presented in Table 1 and Table 2. There were no significant main effects of side ($F_{1,13} = 0.140$, $p = 0.715$), method ($F_{2,12} = 0.714$, $p = 0.509$) or day ($F_{2,12} = 1.543$, $p = 0.253$) on the plantar fat pad thickness values and no significant interactions among any of the variables.

ICCs (model 3,1) for the midfoot plantar fat pad thickness data obtained using the three different ultrasound methods for the first day of testing ranged from 0.82 to 0.93 (Table 3). ICCs (model 3,2) representing the data obtained over two and three consecutive days for each of the 3 ultrasound methods ranged from 0.85 to 0.94 (Table 4). Overall, the ICC values ranged from 0.82 to 0.94, the SEM values ranged from 0.12

Table 1. Plantar fat pad thickness (mean \pm SD [range]) of the children's feet for three methods*.

Side/Ultrasound Method	Thickness (mm)
Right foot	
Method 1	3.9 \pm 0.4 (3.3-4.4)
Method 2	3.9 \pm 0.6 (3.2-5.1)
Method 3	3.9 \pm 0.6 (3.1-4.9)
Left foot	
Method 1	3.9 \pm 0.6 (3.1-4.9)
Method 2	3.9 \pm 0.6 (3.1-5.0)
Method 3	3.8 \pm 0.5 (3.1-4.8)

* *There was no significant difference in the medial fat pad thickness values obtained for either of the children's feet for any of the three methods. The data are the average of two trials on day one*

Table 2. Mean (\pm SD) plantar fat pad thickness (mm) values for the three methods, for the three days for each side (right and left) of the children (n = 14).

Side/Ultrasound Method	Trial 1	Day 1		Day 2	Day 3
		Trial 2	Mean*	Mean*	Mean*
Right foot					
Method 1	3.9 \pm 0.4	3.9 \pm 0.5	3.9 \pm 0.4	3.9 \pm 0.5	3.9 \pm 0.5
Method 2	3.9 \pm 0.6	3.9 \pm 0.6	3.9 \pm 0.6	3.9 \pm 0.6	3.9 \pm 0.6
Method 3	3.9 \pm 0.7	3.9 \pm 0.6	3.9 \pm 0.6	3.9 \pm 0.5	3.9 \pm 0.6
Left foot					
Method 1	3.9 \pm 0.6	3.9 \pm 0.6	3.9 \pm 0.6	3.8 \pm 0.5	4.0 \pm 0.6
Method 2	3.9 \pm 0.6	3.9 \pm 0.7	3.9 \pm 0.6	3.8 \pm 0.6	4.0 \pm 0.7
Method 3	3.9 \pm 0.5	3.8 \pm 0.5	3.8 \pm 0.5	3.8 \pm 0.5	3.9 \pm 0.5

* *The mean of day 1, 2, and 3 is based on two measurements each day*

Table 3. Plantar fat pad thickness reliability for the first day of testing for the three methods.

Side/Ultrasound Method	ICC (CI, 95%)	SEM	SRD
Right foot			
Method 1	0.83 (0.49-0.95)	0.16	0.5
Method 2	0.85 (0.56-0.95)	0.20	0.6
Method 3	0.90 (0.70-0.97)	0.17	0.5
Left foot			
Method 1	0.89 (0.67-0.96)	0.18	0.5
Method 2	0.82 (0.45-0.94)	0.23	0.7
Method 3	0.93 (0.80-0.98)	0.15	0.5

Abbreviations: CI, confidence interval; ICC, intraclass correlation coefficient (model 3,1); SEM, standard error of the measurement(mm); SRD, smallest real difference(mm)

Table 4. Inter-day plantar fat pad thickness reliability for measurements made on either two or three consecutive days.

Ultrasound Method	Right Foot			Left Foot		
	ICC (CI, 95%)	SEM	SRD	ICC (CI, 95%)	SEM	SRD
3 Consecutive Days						
Method 1	0.87 (0.73-0.96)	0.16	0.5	0.92 (0.80-0.97)	0.15	0.5
Method 2	0.86 (0.66-0.95)	0.20	0.6	0.93 (0.83-0.98)	0.16	0.5
Method 3	0.92 (0.80-0.97)	0.15	0.5	0.89 (0.74-0.96)	0.16	0.5
2 Consecutive Days						
Method 1	0.93 (0.78-0.98)	0.13	0.4	0.85 (0.56-0.95)	0.20	0.6
Method 2	0.86 (0.57-0.95)	0.20	0.6	0.89 (0.67-0.97)	0.20	0.6
Method 3	0.94 (0.82-0.98)	0.12	0.4	0.85 (0.54-0.95)	0.18	0.5

*Abbreviations: CI, confidence interval; ICC, intraclass correlation coefficient (model 3,2); SEM, standard error of the measurement (mm); SRD, smallest real difference(mm)
The data are the average of two trials taken each day*

to 0.23 mm, and the SRD values ranged from 0.4 to 0.7 mm, which indicated that the three methods provided good reliability (11). No substantial differences in reliability were evident among the three methods.

Discussion

This investigation confirms that ultrasonography is a reliable field tool to measure the thickness of the midfoot plantar fat pad in young children. Ultrasound systems have previously been used to measure plantar tissue thickness under the metatarsal heads in both older children (1.1 to 2.6 mm; 12) and adults (13). Skin and plantar aponeurosis thickness values recorded beneath the metatarsal heads in older children, are lower than the average medial midfoot fat pad thickness measured for the right and left feet of the 14 children in the present study (Table 1), suggesting that greater fat padding may be evident beneath the midfoot region. However, soft tissue thickness values of the medial aspect of the navicular measured using ultrasound in newborn and infant feet (12 months of age), with mean values of 4.7 and 7.6 mm, respectively (14), are greater than the medial midfoot fat pad thicknesses of the present subjects. Irrespective of these between-study differences, results of the present study confirm that a medial midfoot plantar fat pad exists in the feet of children aged 2.4-5.3 years of age, with mean fat pad values between 3.8 mm to 3.9 mm (range, 3.0 to 5.1 mm), depending upon the method used to make the measurement.

Good within-day and between-day reliability was demonstrated for all three methods. However, large confidence intervals were noted and may be attributable to the small sample size. To measure variability within a subject, both SEM and SRD indexes were calculated. A comparison of the SEM for the first day of testing (Table 3) indicated that greater variation occurred during method 2; however, measures were consistent between feet for all methods. As no studies could be located with which to compare SEM range, further research is necessary. The SRD ranged from 0.4 to 0.7 mm, with an average SRD of 0.5 mm, indicating that this value constituted a real difference measurable within subjects. All three ultrasound methods were therefore

sensitive enough to detect changes in fat pad thickness beneath the medial midfoot. Measurements collected over two and three consecutive days indicated that the data were stable over time with no learning effect or systemic bias apparent (Table 4).

Although the fat pad thickness for the three methods did not significantly differ, the data collection procedures for methods 2 and 3 were more complex and time-consuming than method 1 as they required the transducer to be moved along the plantar surface of the foot, using bony landmarks to guide final placement of the transducer. Conversely, method 1 was more time efficient, as it involved placement of the transducer directly in line with a pre-identified landmark on the dorsal surface of the navicular. Collecting ultrasound data from young children, who are often reluctant to sit motionless for very long, requires both time-efficiency (examiner) and patience (examiner and subject). The time-efficient protocol used for method 1 facilitated child compliance in terms of the requirement to remain motionless during data collection. Direct placement of the ultrasound transducer onto the plantar surface of the foot beneath the dorsal-navicular landmark is, therefore, recommended as the most appropriate procedure to measure the thickness of the midfoot plantar fat pad in young children. As no significant differences were found between thickness values for the children's right and left feet, thickness values obtained for either foot could be used to represent a child's medial midfoot fat pad thickness. However, whether this between-foot uniformity remains as children age requires further investigation.

Although there is consensus of opinion regarding the existence of fat padding beneath the longitudinal arch in newborns and infants, the changes in, or the possibility for disappearance of, this padding as children develop remain questionable. Now that it has been proven reliable, the current ultrasound method described could be used to characterise development of the midfoot fat pad in children to establish whether and

when this padding disappears or whether it remains as perhaps a protective mechanism for the longitudinal arch, particularly in the feet of overweight and obese children.

Conclusion

This investigation confirms that ultrasonography is a reliable imaging method to quantify medial midfoot plantar fat pad thickness in young children. It is recommended that direct placement of the ultrasound transducer onto the plantar surface of the child's foot beneath the dorsal-navicular landmark is a reliable and time-efficient procedure.

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Chapter 3

Are the feet of obese children fat or flat? Revisiting the debate

This chapter is an amended version of the manuscript: Riddiford-Harland DL, Steele JR, Baur LA. Are the feet of obese children fat or flat: Revisiting the debate. *International Journal of Obesity* 2010; doi:10.1038/ijo.2010.119.

Abstract

Objective: There is debate as to the effects of obesity on the developing feet of children. We aimed to determine whether the flatter foot structure characteristic of obese primary school-aged children was due to increased medial midfoot plantar fat pad thickness (fat feet) or due to structural lowering of the longitudinal arch (flat feet).

Methods and Procedures: Participants were 75 obese children (8.3 ± 1.1 y, 26 boys, BMI 25.2 ± 3.6 kg/m²) and 75 age- and sex-matched non-obese children (8.3 ± 0.9 y, 15.9 ± 1.4 kg/m²). Height, weight and foot dimensions were measured with standard instrumentation. Medial midfoot plantar fat pad thickness and internal arch height were quantified using ultrasonography.

Results: Obese children had significantly greater medial midfoot fat pad thickness relative to the leaner children during both non-weight-bearing (5.1 mm and 4.6 mm, respectively; $p < 0.001$) and weight-bearing (4.7 mm and 4.3 mm, respectively; $p < 0.001$). The obese children also displayed a lowered medial longitudinal arch height when compared to their leaner counterparts (23.5 mm and 24.5 mm, respectively; $p = 0.006$).

Conclusion: Obese children had significantly fatter *and* flatter feet compared to normal-weight children. The functional and clinical relevance of the increased fatness and flatness values for the obese children remains unknown.

Introduction

As feet are the body's base of support, healthy foot structure is critical for efficient posture and ambulation. Studies investigating the effects of obesity during childhood on the development of foot structure have typically used an indirect measure, that of footprints, to suggest that the feet of young obese children are characteristically flatter relative to their leaner counterparts (1-5). This flatter foot appearance has been assumed to be a function of lowered arches within the feet, which, in turn, may lead to musculoskeletal disorders and pain in the back and lower limbs of obese children and adolescents (6,7). There is growing debate in the literature, however, as to whether this flatter foot structure does actually constitute lowered arches.

One suggestion is that the flatter feet characteristic of obese children may merely be caused by the existence of a thick plantar fat pad underneath the medial midfoot, giving the appearance of a flat foot due to greater ground contact (4). Although a fat pad is typically present under the medial aspect of the feet of infants at birth, this fatty pad is thought to disappear in the juvenile foot between 2 and 6 years of age following major developmental changes in the medial arch contour (8,9). A recent study confirmed thicker fat padding in the feet of obese, compared to overweight, school-aged children, although as the between-group difference was small, no functional relevance was attributed to this increased fat pad thickness (10). However, in a study comparing pre-school children (3) no difference in medial fat pad thickness was found between overweight/obese and non-overweight participants. As significant between-group

differences were evident in external arch height measures in these two previous studies, the authors postulated that obese children's feet were structurally flatter, rather than fatter, than those of their leaner counterparts. Limitations of these studies, however, included small sample sizes, the absence of normal-weight control participants in the first study, and the participants' young age (mean age 4.3 y) confounding interpretation of the results in the second study.

To our knowledge, no study has systematically investigated medial midfoot fat padding and medial longitudinal arch height in the feet of a large sample of lean and obese children aged more than 5 years. Therefore, in this study we aimed to determine whether, in comparison with normal-weight children, the flatter foot structure characteristic of obese school-aged children was due to increased medial midfoot plantar fat pad thickness (fat feet) or due to structural lowering of the longitudinal arch (flat feet).

Methods

Participants

Participants in this study were recruited by two strategies. The first involved a cohort of children who had volunteered to participate in a multi-site randomized controlled trial of a combined physical activity skill-development and dietary modification program among overweight and obese children (11); in this case, measurements were taken at baseline. In addition, four local independent schools granted permission to recruit children in Kindergarten through to Year 3. From these two samples, all obese children ($n = 75$) were selected as experimental participants, with 75 non-obese children, matched for age and sex to the obese children, selected as control participants. As arch height was measured in this study, and this foot parameter

is believed to be formed by about 6 years of age (8,9), only data for children who were 6 years or older were analysed and included in the results. It is recognised, however, that foot development rate will differ between children and may be completed prior to or later than 6 years of age.

All measurements were collected at either the University of Wollongong or the child's school. The University of Wollongong Human Research Ethics Committee approved all study procedures [HE05/010] and parents gave written, informed consent for their children to participate in the study. All children gave verbal consent to participate.

Anthropometry

Participants had their standing height and body mass recorded while wearing lightweight clothing. Standing height was measured to the nearest 0.1 cm using a Seca 214 portable stadiometer (Seca Corp., Hanover, MD, USA) and a set of UC-321 Home Health Care Scales (A&D Weighing Pty Ltd., Thebarton, SA, Australia) was used to measure body mass to the nearest 0.01 kg. The mean scores of two height and two body mass measurements were used to calculate body mass index (BMI; $\text{weight}/\text{height}^2$). If measurements differed by more than 0.3 cm (height) or 0.03 kg (body mass) a third measure was taken and the closest two measures were used to calculate the mean score. The classification system proposed by Cole et al. (12), based upon BMI, was used to determine children's weight status.

External Foot Measures

Foot length, ball of foot length, instep length, ball of foot breadth, heel breadth, ball of foot height, dorsal arch height, plantar arch height, ball of foot circumference and instep circumference were measured for both feet of each participant to the nearest millimetre. All anthropometric foot measurements (13) were recorded by the chief

investigator [DLRH] using a combination level (Stanley Tools, New Britain, CT, USA), a metal tape (KDS Corp., Kyoto, Japan), small anthropometer (Lafayette Instrument Co., Lafayette, IN USA) and a custom-designed foot tray. Specifically, the plantar arch height was measured from the supporting surface to the lowest medial foot protrusion at the instep landmark (13). Two measurements (three, if values differed by 3 mm) were taken while participants stood barefoot with equal weight on both feet. The mean score was used in later analysis to represent each foot dimension.

Internal Foot Measures

A portable SonoSite® 180PLUS ultrasound system (Washington, USA) with a 38 mm broadband linear array transducer (10-5 MHz, 7 cm maximum depth) was used to quantify plantar fat pad thickness (mm) in the medial midfoot region of each child's right and left foot (14). A linear transducer with a high frequency was selected as it provides a uniform, wide field of view with a superior near-field resolution for imaging superficial structures (15), such as adipose tissue. Ultrasound was selected as it was non-invasive, portable for use in the field and did not involve radiation.

Non-weight-bearing plantar fat pad thickness was assessed while each child was seated with their leg extended and foot resting in a relaxed position on the lap of the chief investigator [DLRH], who took all measurements. To standardise the site at which the midfoot plantar fat pad thickness was assessed, the ultrasound probe was placed longitudinally, vertically below the dorsal navicular landmark on the plantar surface of the foot and aligned with the second metatarsal. When a clear image was attained, the system was paused and the thickness of the fat pad was quantified to the nearest 0.01 cm using the measurement function of the ultrasound system (Figure 1). Three trials were collected with the mean thickness value per foot taken as representative of left and right medial midfoot plantar fat pad thickness. Weight-

bearing fat pad thickness and internal arch height were assessed following the same protocol but with the children standing on a custom-designed Perspex platform. Internal arch height, measured at the same site as the fat pad thickness measurement, was the distance from the supporting surface of the platform to the joint beneath the dorsal navicular land mark. Children were assisted onto the platform and focussed on a picture placed directly in front of them and at eye level. They were instructed to stand with equal weight on each foot and their hands at their sides. The probe was held in a cut-out section (80 mm x 25 mm) of the platform surface, which allowed the probe to be placed level with the supporting surface of the platform to image the child's medial midfoot whilst they were standing (Figure 2). Extensive reliability testing of this novel method was performed on three consecutive days, three times per foot, for 14 children unassociated with the current study. Intraclass correlation coefficients (ICC; 16) on the between-day values ranged from 0.82 to 0.91, confirming the method provided highly reproducible values (14).

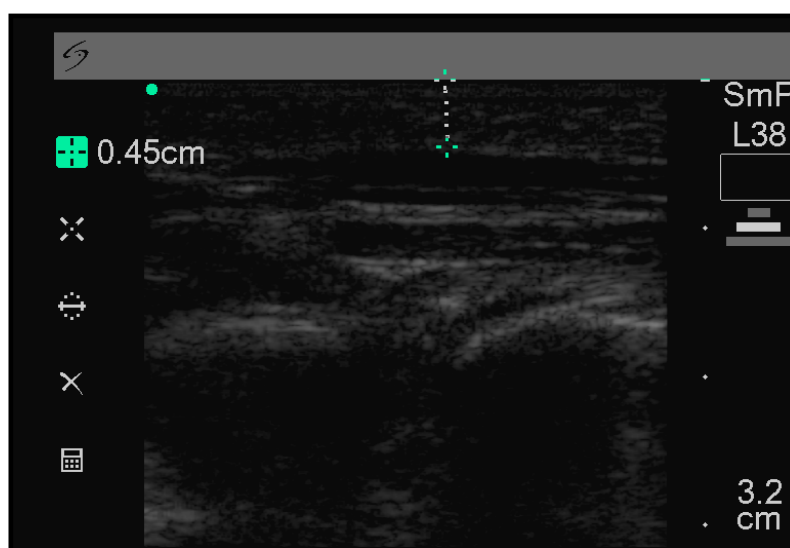


Figure 1. An example of an ultrasound image of the medial midfoot fat pad thickness measured during non-weight-bearing.



Figure 2. Experimental set up used to measure medial midfoot plantar fat pad thickness during weight-bearing.

Statistical Analysis

Initial analysis of the data revealed limited significant differences in the outcome variables between the right and left feet of each child. Therefore, data for the left foot were selected as representative of each child's foot structure and data pertaining to that foot were included in the statistical analyses for between-subject group comparisons. Means and standard deviations for each variable were calculated for the two subject groups. Data were tested for normality using a Kolmogorov-Smirnov test (with Lilliefors' correction) with a Mann-Whitney U-test employed if the assumption of normality was violated. Independent *t*-tests were then computed on data obtained for the obese children relative to the non-obese children to determine whether there were any significant differences ($p \leq 0.05$) in the outcome variables characterising foot structure between the two subject groups. The software package SPSS 15 for Windows (SPSS Inc., Illinois, USA) was used to perform all statistical analyses.

Results

As can be seen in Table 1, the obese children were significantly taller with a greater BMI compared to the non-obese children yet there was no difference in age, which ranged from 6.4 to 9.9 years. Table 1 also shows the external foot anthropometry for the two groups, and internal foot measures are shown in Figure 3. As anticipated, the obese children's feet displayed significantly greater values for all lengths, breadths, heights and circumferences when compared to the feet of the non-obese children. The only external foot anthropometric measurement not significantly different between the two groups was plantar arch height (Table 1).

Both the non-weight-bearing and weight-bearing medial midfoot fat pads were significantly thicker in the obese children compared to their lean counterparts, while the internal arch height was significantly lower in the feet of the obese children (Figure 3).

Table 1. Description and external foot anthropometry (mean \pm SD) of the sample.

Variables	Obese (n=75)	Non-obese (n=75)	<i>p</i> -value*	Range
Age (y)	8.3 \pm 1.1	8.3 \pm 0.9	0.944	6.4 - 9.9
BMI (kg/m ²)	25.2 \pm 3.6	15.9 \pm 1.47	<0.001	12.4 - 37.4
Weight (kg)	48.6 \pm 11.6	26.3 \pm 4.7	<0.001	16.5 - 77.6
Height (m)	1.37 \pm 0.08	1.29 \pm 0.08	<0.001	1.08 - 1.58
Foot length (mm)	214 \pm 15	197 \pm 15	<0.001	162 - 250
Ball of foot length (mm)	156 \pm 11	143 \pm 11	<0.001	120 - 182
Instep length (mm)	108 \pm 10	104 \pm 9	0.014	81 - 131
Ball of foot breadth (mm)	87 \pm 7	76 \pm 6	<0.001	60 - 104
Heel breadth (mm)	57 \pm 5	50 \pm 4	<0.001	41 - 68
Ball of foot height (mm)	36 \pm 5	33 \pm 3	<0.001	26 - 66
Dorsal arch height (mm)	64 \pm 6	60 \pm 5	<0.001	50 - 78
Plantar arch height (mm)	14 \pm 3	14 \pm 2	0.798	7 - 24
Ball of foot circumference (mm)	217 \pm 16	190 \pm 14	<0.001	163 - 267
Instep circumference (mm)	217 \pm 16	185 \pm 13	<0.001	160 - 258

*indicates a significant between-subject group difference ($p < 0.05$)

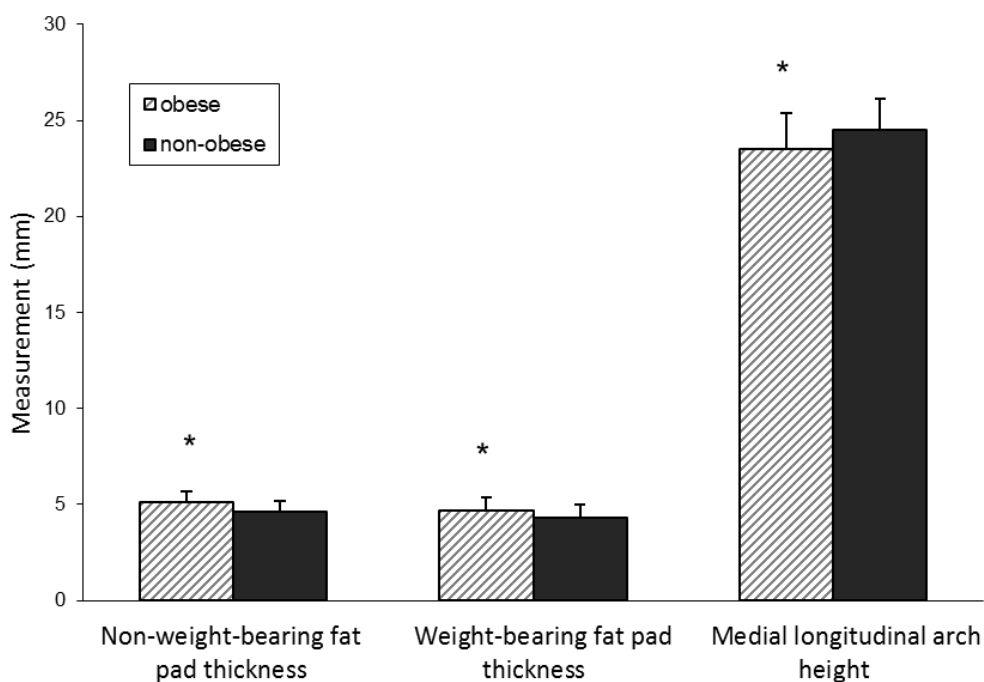


Figure 3. Internal foot measures (mean \pm SD) for the obese ($n = 75$) and non-obese ($n = 75$) children. * Significant between-subject group difference ($p < 0.05$).

Discussion

In this study we examined foot dimensions in primary school-aged children to determine whether obese children displayed increased plantar fat pad thickness or lowered medial longitudinal arches compared to their lean counterparts. Significant differences were found in almost all foot measurements between the obese and non-obese children.

External Foot Measures: Previous investigation of school-aged children has confirmed that obese children have larger foot dimensions when compared to their non-overweight peers (2), findings which are consistent with results from the current study. However, unlike younger overweight and obese children (3), the obese children in the present study had significantly higher feet relative to the feet of the non-obese children. The obese children's feet were higher at the point where the upper surface of the foot

meets the leg (dorsal arch) and also higher at the front of the foot (ball of foot). It could be assumed that if the tops of the obese children's feet were significantly higher than their lean counterpart's feet then their plantar arches should also be significantly higher. However, the height of the plantar arch was similar in both groups. This suggests either a lowering of the midfoot arch or advanced bone structure development in the feet of obese children relative to leaner children, although evidence on this latter explanation is still conflicting (17).

Numerous studies have attempted to address the issue of comparing medial longitudinal arch height between subject groups by normalising arch height to foot length or truncated foot length to produce an arch index (18,19). Because of the significant differences in 9 of the 10 foot anthropometry measures between the two groups in the present study, plantar arch height (the only non-significant value) was divided by truncated foot length to further investigate this finding. When normalised to truncated foot length (the length from the midpoint of the heel to the apex of the foot minus the big toe), the plantar arch index was significantly less in the obese children compared to the non-obese children (mean \pm SD, 0.09 ± 0.02 and 0.10 ± 0.02 , respectively, $p < 0.001$). This indicates that even though the obese children had a higher foot, they also had a lower medial midfoot compared to the non-obese children. On first inspection, these results appear to confirm the notion that obese children's feet are flatter than their non-obese counterparts. However, the question then arises as to whether external medial midfoot height, an indirect measurement, is a good indication of bone height or foot development and, in turn, representative of flatter feet in the obese participants, or is this measure influenced by additional adipose tissue in this region of the foot, indicating that the obese children's feet were just fatter?

Internal Foot Measures: This is the first study to quantify and report midfoot plantar fat pad data for a relatively large sample of lean and obese school-aged children. Similar to results reported previously for both pre-school children (3) and overweight and obese school-age children (10), all children in the present study, irrespective of their BMI, displayed a midfoot plantar fat pad, with the thickness of this fat pad ranging from 2.9 to 6.9 mm. Therefore, we are able to confirm that, in contrast to speculation in the literature (8,9), the plantar fat pad does not disappear in the juvenile foot following developmental changes in the medial arch contour.

The difference in non-weight-bearing medial midfoot fat pad thickness between the two groups (mean difference of 0.5 mm) was the same as that previously reported between overweight and obese children (10), confirming that the obese children had fatter feet relative to their non-obese counterparts. A study in younger children (mean age 4.3 y) showed an insignificant difference of 0.2 mm between obese and non-obese participants (3). Such findings would suggest that there is an association between age, obesity and fat pad thickness, whereby as a child's foot develops, the effects of obesity on fat pad thickness become more apparent and that fat pad thickness may increase with increasing body mass in obese children but remain stable in non-obese children. This notion is speculative and requires investigation. Furthermore, the functional relevance of a 0.5 mm difference in non-weight-bearing fat pad thickness is unknown (10). However, previous studies that have quantified the thickness of tissue structures within the feet have claimed tissue thickness differences of 0.4 mm to be clinically relevant (20).

Interestingly, even upon weight-bearing, the between-subject group differences in fat pad thickness were still evident (mean difference of 0.3 mm) and the fat pad of the obese children compressed significantly more than did the fat pad of the non-obese

participants. As the values for weight-bearing fat pad thickness were of similar size and difference to those seen during non-weight-bearing, we speculate that fatty tissue in the midfoot region serves no functional purpose to the developing boney architecture. We therefore postulate that the additional fat padding evident in the midfoot in obese school-aged children is more a reflection of the children's excess adiposity rather than an adaptation to protect the development of the medial longitudinal arch.

Although previous studies have investigated internal arch height using radiography (7,21) and CT scans (22), no studies could be located which have utilised ultrasonography as a non-invasive and inexpensive measurement tool for medial longitudinal arch height in either children or adults. The only published radiographic investigation of children's feet was a study of older children during weight-bearing in which the obese participants displayed a lower internal arch height than their non-obese counterparts (7). In the present study, young obese children also displayed a significantly lower internal arch height relative to the non-obese children. This significant difference was still apparent when calculated as an index with truncated foot length ($p < 0.001$). Based on these results it appears that, due to the need to continually carry extra body mass, the medial longitudinal arches in the feet of obese young children remain lower than in the feet of lean children as these children get older. The functional relevance of these lower structural parameters and the resultant extent of damage to the developing feet of young obese children warrant investigation.

This is the first study to explore medial plantar fat pad thickness and internal plantar arch height in obese and non-obese school-aged children. The results highlight that obese children have significantly fatter and flatter feet compared to their lean counterparts. However, the functional and clinical relevance of the increased fatness and flatness values in obese children remains unknown. Longitudinal research is

therefore needed to ascertain the long-term effects of obesity on the structure of the medial longitudinal arch and to determine whether there are functional complications in the feet of obese individuals associated with their continual bearing of excess mass during childhood and beyond. Finally, there is a need for studies investigating the effects of obesity interventions in childhood on the structure and function of children's feet.

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Chapter 4

Medial midfoot fat pad thickness and plantar pressures: Are these related in children?

This chapter is an amended version of the manuscript: Riddiford-Harland DL, Steele JR, Baur LA. Fat feet and plantar pressures: Are these related in children? *International Journal of Pediatric Obesity*. Resubmitted for publication 11 November, 2010.

Abstract

Objective: Previous research has shown that obese children have thicker plantar fat pads compared to non-obese children. As it is uncertain how this thickness influences dynamic foot function, this study aimed to investigate the relationship between dynamic plantar pressures generated beneath the feet of school-aged children and their medial midfoot fat pad thickness measures.

Methods and Procedures: Height and weight were measured, and BMI calculated, for 252 children aged 6.0 - 9.9 y (mean \pm SD 8.1 \pm 1.0 y, 112 boys). Medial midfoot plantar fat pad thickness was quantified using ultrasonography and dynamic plantar pressure distributions were measured using a pressure platform. Data were correlated to establish the strength of the relationships among BMI, plantar fat pad thickness and medial midfoot plantar pressures.

Results: Both medial midfoot plantar fat pad thickness and medial midfoot plantar pressure were significantly correlated with BMI ($r = 0.401$, $p < 0.001$ and $r = 0.465$, $p < 0.001$, respectively). Although medial midfoot plantar pressure significantly correlated

with midfoot plantar fat pad thickness during non-weight-bearing ($r = 0.294, p < 0.001$) and weight-bearing ($r = 0.289, p < 0.001$), the strength of the relationships were low.

Conclusion: Additional medial midfoot fat padding in obese school-aged children appears to reflect their excess body mass rather than an adaptation to cushion pressures associated with this increased body mass. Further investigation is required to identify probable short- and long-term functional limitations resulting from increased pressures generated beneath the feet of obese children when walking.

Introduction

Childhood obesity is now recognised as a significant risk factor for the development of musculoskeletal functional disabilities (1-5), with an increasing number of studies having investigated the effects of childhood obesity on the body's base of support, the feet (6-10). This research has consistently shown that, when compared to non-overweight children of the same age, overweight and obese children generate significantly higher ground reaction forces while walking as a consequence of their increased body mass and, in turn, generate higher pressures beneath their feet, despite an increased foot/ground contact area (7,11-13). Researchers have predicted the possibility of future structural and functional complications to the feet of these overweight and obese children, should these children remain overweight (7-9). However, it has also been speculated that the body might attempt to compensate for the higher forces generated as a result of excess mass. For example, we recently showed that the medial midfoot plantar fat pad under the feet of obese children was significantly thicker than the fat pad of non-obese children (14). Despite this finding, there has been no systematic investigation into the relevance of this increased plantar fat pad thickness with respect to foot function (14).

In adults, a functional link has been proposed between increased plantar pressure distributions displayed by obese individuals and greater foot pain on weight-bearing and during physical activity (15). As obese children tend to become obese adults (1), the prognosis is not good for these children to participate in physical activity if their feet cannot compensate for their excess mass. If, however, the thicker plantar fat pad evident in overweight and obese school-aged children (14) can assist to cushion the higher plantar pressures generated beneath their feet and thereby support the medial longitudinal arch, the high plantar pressure distributions displayed by obese children may have little, if any, functional relevance. As this has not been investigated, the aim of the present study was to determine the relationship between medial midfoot fat pad thickness and dynamic plantar pressure distributions beneath the feet of children aged between 5 and 9 years. We hypothesised that there would be a significant positive correlation between obesity, as characterised by body mass index (BMI), and both medial midfoot fat pad thickness and medial midfoot plantar pressure distribution.

Methods

Participants and Recruitment Processes

Two hundred and fifty three children, between the ages of 6.0 and 9.9 years, volunteered to participate in this study. One hundred and eighty three children were recruited from local independent primary schools in the Wollongong region of New South Wales, Australia. A further 70 children were recruited at baseline from Wollongong, New South Wales, one site of a multi-site randomized controlled trial of a combined physical activity skill-development and dietary modification program among overweight and obese children (16,17).

The independent schools' governing authority granted permission for the authors to approach 12 schools in the local area, of which 33% of school principals consented to their school's involvement. Information packages were then distributed to all children in Grades 1, 2 and 3 (aged 5 to 9 years). School participation ranged from between 30 to 64%, with all consenting children being measured (17.6% were overweight or obese as categorised by Cole et al., 18; none was extremely obese, 16). Data for one participant were excluded from analysis due to a congenital foot deformity, which may have influenced results.

The recruitment process for the controlled trial (explained in detail elsewhere; 16), from which the 70 children were measured at baseline, included telephone communication with, and information sent to, local schools, general practitioners, hospital clinics, and posters placed in public areas. The University of Wollongong's Media Unit organised media releases, which resulted in advertisements in the local print media, radio broadcasts and television coverage. Families were encouraged to contact the study investigators if interested. Children were included in the intervention program if they were between 5.5 and 9.9 years of age, generally healthy, were pre-pubertal and overweight/obese. Extreme obesity, syndromal causes of obesity, long term steroid use, use of medications that may cause weight gain, chronic illness and significant dietary restrictions comprised the exclusion criteria (19).

Parents gave written, informed consent for their children to participate and all children gave verbal consent to participate. Data collection occurred at either the child's school or the University of Wollongong. All study procedures were approved by the University of Wollongong Human Research Ethics Committee [HE05/010].

Anthropometry

Standing height was measured to the nearest 0.1 cm (Seca 214 portable stadiometer, Seca Corp., Maryland, USA or PE87 portable stadiometer, Mentone Educational Centre, Victoria, Australia) and body mass was recorded to the nearest 0.01 kg (UC-321 Home Health Care Scales, A&D Mercury Pty Ltd., South Australia, Australia or Tanita HD464 scales, Tanita Corporation of America Inc, Illinois, USA). All instrumentation was calibrated using standard procedures prior to data collection. Two height and two body mass measurements were averaged and used to calculate body mass index (BMI; $\text{weight}/\text{height}^2$). Mean BMI z-score was also calculated to account for age (16). It is acknowledged that BMI is a measure of body mass in relation to height rather than body fatness. However, BMI was selected due to the participant age-range and the large number of participants to be measured in the field. Furthermore, BMI has been consistently used as an indicator of overweight and obesity in children (20). Anthropometry was recorded with participants barefoot and wearing lightweight clothing.

Midfoot Plantar Fat Pad Thickness

Plantar fat pad thickness (mm) in the medial midfoot region of each child's right and left foot (21) was quantified using a portable SonoSite® 180PLUS ultrasound system (Washington, USA) with a 38 mm broadband linear array transducer (10-5 MHz, 7 cm maximum depth). A high frequency linear transducer was selected as it provides a uniform, wide field of view with a superior near-field resolution for imaging superficial structures (22), such as adipose tissue. Ultrasonography provided a direct measurement tool of plantar fat pad thickness that was non-invasive, portable for use in the field and did not involve radiation.

All plantar fat pad measurements were collected by the chief investigator [DLRH]. To assess non-weight-bearing plantar fat pad thickness, each child sat in a relaxed position with the test foot resting on the lap of the chief investigator. To standardise the site at which the midfoot plantar fat pad thickness was assessed, the ultrasound transducer was placed longitudinally on the plantar surface of the foot directly below the dorsal navicular landmark. The transducer was also aligned with the second metatarsal in the sagittal plane (Figure 1). The system was paused when a clear image was attained and the thickness of the fat pad was quantified to the nearest 0.01 cm using the measurement function of the ultrasound system. Three trials were collected with the mean thickness value per foot taken as representative of left and right medial midfoot plantar fat pad thickness. Weight-bearing fat pad thickness was assessed following the same protocol but with the children standing on a custom-designed Perspex platform. To obtain weight-bearing images, the transducer was held in an 80 mm x 25 mm cut-out section of the platform and level with the platform surface (14). Extensive reliability testing of this novel method to quantify medial midfoot plantar fat pad thickness was performed on three consecutive days, three times per foot, for 14 children not associated with the current study (21). Intraclass correlation coefficients (ICC; 23) on the between-day values ranged from 0.82 to 0.91, confirming the method provided highly reproducible midfoot plantar fat pad thickness values (21).

Plantar Pressure Distribution

Dynamic plantar pressure distributions generated underneath each child's feet were quantified as the children walked over a calibrated emed® AT-4 pressure system (Novel_{gmbh}, Munich, Germany), which was placed on a firm, level surface and embedded midway along a high-density foam walkway (3 m x 1 m). The two-step method was used to quantify plantar pressures as its use is preferable if subjects



Figure 1. Placement of the ultrasound transducer to collect a non-weight-bearing image of the medial midfoot plantar fat pad.

fatigue easily (24) and, compared to the mid gait method, young children have a better chance of striking the platform without the need for excessive repeated trials when using the two-step method (24,25). Initially, an accompanying walker held each child's hand and walked beside them in order for the children to walk at a consistent pace. These familiarisation trials were performed to limit targeting of the pressure platform, to enable the children to become accustomed to the walking pace set by the accompanying walker and to ensure that each child was comfortable with the experimental procedures, before data were collected for three successful trials for each foot. The subjects did not hold the accompanying walker's hand during actual data collection.

The dynamic plantar pressure footprints generated by each child were divided into 10 regions (26) and masked using Novel-ortho automask software (Novel_{gmbh}, Munich, Version 13.3.16). The mean peak pressure footprints were then analysed using Novel-win multimask software (Novel_{gmbh}, Munich, Version 13.3.16) to determine the

maximum contact area (cm²), maximum force (N), and peak pressure (kPa) in each of the masked areas.

Statistical Analysis

No significant differences between the children's left and right feet were found following initial analysis of the outcome variables. Due to an incomplete dataset for the right foot, the left foot was selected as representative of each child's foot characteristics and data pertaining to that foot were included in the statistical analyses. Pearson product moment correlation coefficients were calculated to determine the strength of relationships among the primary outcome variables of medial midfoot plantar fat pad thickness, midfoot plantar pressures and adiposity (characterised by BMI and BMI z-score). All statistical analyses were conducted using SPSS software (SPSS Inc., Illinois, USA).

Results

Descriptive characteristics of the 252 participants, including their medial midfoot fat pad thickness measurements, are presented in Table 1. Table 2 lists contact area, force and peak pressure data generated for the 10 foot regions by the participants. The relation between midfoot fat pad thickness and medial midfoot peak plantar pressure is depicted in Figure 2 whereas the relation between plantar pressure and BMI is included in Table 2.

Medial midfoot peak plantar pressure was significantly and positively correlated with BMI and BMI z-score (pressure $r = 0.465$ and $r = 0.480$, respectively). Both non-weight-bearing and weight-bearing midfoot plantar fat pad thicknesses were also significantly and positively correlated with BMI ($r = 0.401$ and $r = 0.332$, respectively) and BMI z-score ($r = 0.406$ and $r = 0.323$, respectively). Although significant, only low

level correlations were evident between medial midfoot peak plantar pressure and midfoot plantar fat pad thickness measured when the children were either non-weight-bearing (pressure $r = 0.294$) or weight-bearing (pressure $r = 0.289$; Figure 2).

Table 1. Descriptive characteristics and medial midfoot fat pad thickness values for the sample of children ($n = 252$).

	Mean \pm SD	Range
Age (y)	8.1 \pm 1.0	6.0 – 9.9
Height (m)	1.31 \pm 0.09	1.08 – 1.58
Weight (kg)	33.7 \pm 11.2	16.5 – 70.3
Body mass index (kg/m ²)	19.1 \pm 4.3	12.4 – 34.0
BMI z-score	1.06 \pm 1.4	-2.86 – 3.98
Non-weight-bearing fat pad (mm)	4.8 \pm 0.5	3.2 – 6.9
Weight-bearing fat pad (mm)	4.5 \pm 0.5	2.9 – 6.5

fat pad = medial midfoot fat pad thickness

Table 2. Mean \pm SD for plantar surface contact area (cm²), force (N) and peak plantar pressure (kPa) recorded for the 10 foot regions and their relationships with BMI ($n = 252$).

Foot Region	Contact (cm ²)	Contact & BMI (r)	Force (N)	Force & BMI (r)	Peak Pressure (kPa)	Peak Pressure & BMI (r)
Medial heel	10.6 \pm 2.2	0.826*	139.8 \pm 56.5	0.609*	319.6 \pm 112.8	-0.070
Lateral heel	10.6 \pm 2.2	0.822*	108.7 \pm 44.4	0.647*	265.7 \pm 79.8	0.030
Medial midfoot	2.6 \pm 3.4	0.430*	11.2 \pm 21.6	0.393*	58.3 \pm 31.8	0.465*
Lateral midfoot	11.9 \pm 6.7	0.725*	48.5 \pm 46.9	0.643*	75.8 \pm 38.6	0.697*
Medial forefoot	9.8 \pm 2.4	0.660*	81.4 \pm 20.0	0.456*	178.5 \pm 63.9	0.065
Middle forefoot	7.8 \pm 1.6	0.693*	82.7 \pm 41.6	0.613*	224.2 \pm 79.3	0.455*
Lateral forefoot	16.3 \pm 3.5	0.761*	134.3 \pm 70.9	0.668*	224.6 \pm 93.4	0.573*
Hallux	6.7 \pm 1.4	0.458*	66.9 \pm 39.9	0.287*	249.0 \pm 14.9	-0.410
Toe 2	2.3 \pm 0.6	0.314*	18.8 \pm 16.1	0.222*	115.9 \pm 58.4	-0.142
Toes 3-5	3.9 \pm 1.4	0.175*	14.9 \pm 12.8	0.173*	85.0 \pm 41.3	-0.275*

* indicates a significant correlation ($p < 0.01$)

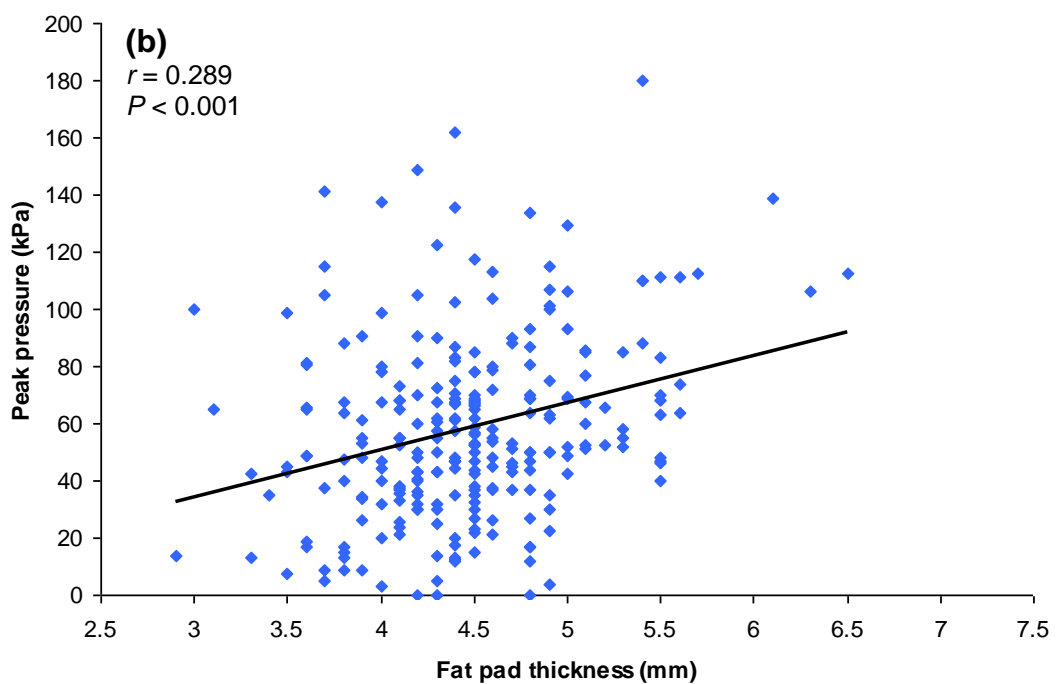
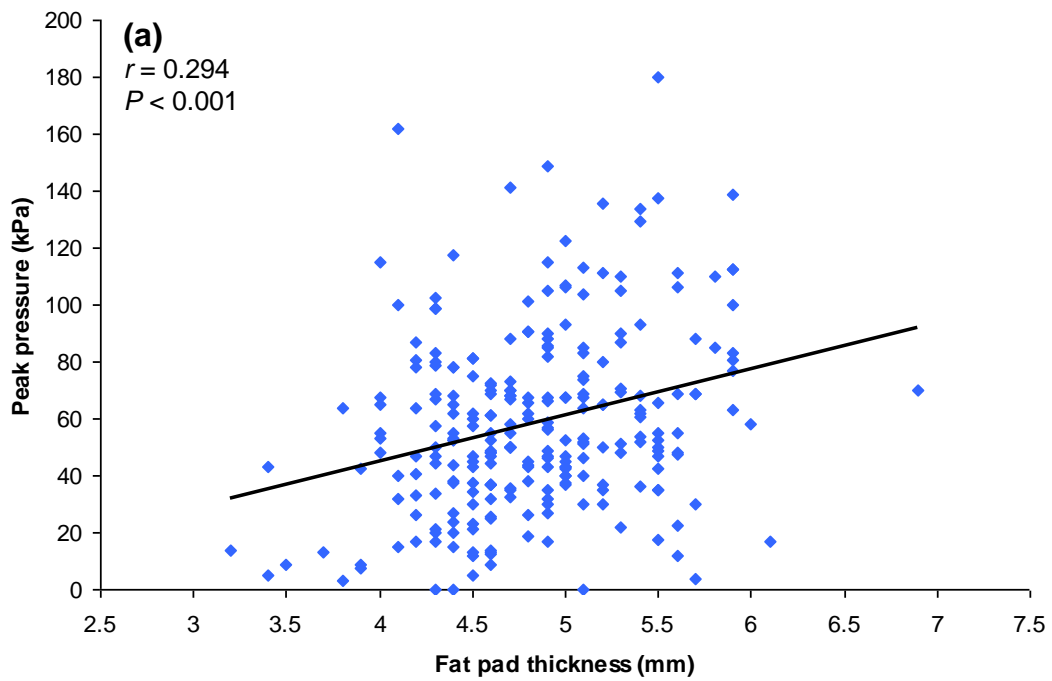


Figure 2. Relationship between (a) non-weight-bearing and (b) weight-bearing medial midfoot plantar fat pad thickness (mm) and medial midfoot peak pressures (kPa) generated when walking by the 252 children.

Discussion

To better understand the effects of obesity on foot function during early development, this study aimed to investigate a large sample of young children to identify the relationship between medial midfoot fat pad thickness and dynamic plantar pressure distributions beneath the feet of school-aged children. Our findings support the notion that higher plantar pressures are associated with increased body mass and that the body does not compensate to reduce possible foot damage.

Regardless of the method used to determine increased body mass, the significant correlation values we identified between BMI/BMI z-score and midfoot plantar pressures and the midfoot fat pad thickness parameters confirmed our hypothesis that increases in obesity levels in children are associated with an increase in both medial midfoot plantar fat pad thickness and midfoot peak plantar pressures. However, these relationships were moderate to low: 21.6% of the variation in peak medial midfoot plantar pressure, and only 16.1% and 11.0% of the variation in midfoot plantar fat pad thickness (non-weight-bearing and weight-bearing, respectively), were accounted for by their relationship with BMI or with BMI z-score: 23.0%, 18.7% and 10.4%, respectively. Interestingly, the correlations between midfoot plantar pressures and medial midfoot fat pad thickness, although low, were positive (Figure 2), implying that a thicker medial midfoot fat pad was actually associated with higher midfoot plantar pressures. It could be argued that, if thick medial plantar fat pads were developed or remained in the midfoot as an adaptation to effectively cushion increased loading associated with excessive mass, thicker fat pads would be associated with lower midfoot plantar pressures as the loads are dissipated by the additional tissue (27).

Irrespective of such an argument, the correlation between midfoot plantar pressures and medial midfoot fat pad thickness was very low, implying that only 8.6%

and 8.4% of the variation in peak plantar pressures generated on the medial midfoot could be accounted for by their relationship with medial midfoot plantar fat pad thickness during non-weight-bearing and weight-bearing, respectively. We therefore postulate that the additional fat padding evident in the midfoot in obese school-aged children is more a reflection of the children's excess body mass rather than an adaptation to cushion loads associated with this increased body mass.

In a recent study from our group comparing overweight/obese children to non-overweight children, matched for age and sex (14), a significant between-subject group difference was noted in the thicknesses of the children's medial plantar fat pads (the fatty tissue beneath the medial longitudinal arch of the foot). The overweight/obese children presented with thicker padding beneath this midfoot region than their leaner peers when measurements were taken in both non-weight-bearing and weight-bearing. The findings of the present study concur with this previous research as a positive correlation was evident between BMI/BMI z-score and the fat pad thickness measure beneath the medial midfoot. Further research should investigate other fatty deposits within the child's feet to determine whether there is consistency in thickness measures with increased BMI. It has been suggested that increased fat pad thickness in the heel reduces sensitivity and elasticity and therefore results in greater plantar pressures (28). Therefore, the histology and function of fat tissue in different areas of the foot requires examination (29).

Foot/ground contact area and peak force beneath all foot regions were significantly and positively associated with BMI, such that as BMI increased, more foot was contacting the ground and greater force was being transmitted through the feet. As BMI increased, significantly higher peak plantar pressures were also evident under the medial and lateral midfoot and middle and lateral forefoot regions, suggesting that the

increase in plantar contact area was not sufficient to compensate for the higher forces in these foot regions as compared to the heel and toes. These results are consistent with previous research (7,12,13) and confirm the effects of obesity in school-aged children on dynamic plantar pressures generated when walking. Excessive loading of the medial midfoot in the present study was assessed if this foot region was in contact with the ground during a dynamic task. Additional foot measurements should be researched in an attempt to better clarify the extent to which the medial longitudinal arch is affected as a result of a greater body mass.

Study limitations include the fact that fat pad thickness measures were taken with participants in a static position and were then correlated with dynamic midfoot function measurements. Better representation of the medial midfoot may be accomplished via ultrasound imaging during a dynamic movement task, such as walking, although these measurement techniques remain technically challenging. Nevertheless, as there is no compensatory mechanism by the body to account for the higher pressures generated as a consequence of greater body mass, the probability of future musculoskeletal complications, including pain and discomfort beneath the foot, in children during activity appears likely (15). The greater the amount of excess adiposity and the longer the exposure to this excessive load, the greater the possibility of injury (5,30).

This is the first study to explore the strength of relationships among BMI, medial plantar fat pad thickness and medial midfoot plantar pressure distribution in school-aged children. Although medial midfoot plantar fat pad thickness and medial midfoot plantar pressure distributions were both significantly correlated with BMI in this sample of young children, the relationship between medial midfoot plantar fat pad thickness and midfoot plantar pressures were low. As the midfoot, in particular the aspect beneath the medial longitudinal arch, has been identified as a potentially vulnerable foot region in

overweight and obese individuals (10,15,31), it is recommended that further research investigate the loading effects of obesity on both static and dynamic foot characteristics. Also, as in the case the medial midfoot, if the lateral midfoot and the middle and lateral forefoot regions of young children cannot compensate for excess body weight during a walking task, the effects of participation in more active tasks warrants investigation.

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Chapter 5

Physical activity and pressure distribution beneath the feet:

Are these factors related in overweight and obese children?

This chapter is an amended version of the manuscript: Riddiford-Harland DL, Steele JR, Baur LA, Cliff DP, Okely AD, Morgan PJ, Jones RA. Physical activity and pressure distribution beneath the feet: Is there a relationship in children? *International Journal of Obesity*. Submitted for publication 7 December, 2010.

Abstract

Objective: To determine the relationships between dynamic plantar pressure distributions and physical activity in overweight and obese school-aged children.

Methods: A cross-sectional design was used to assess 73 5-9 year-old overweight/obese children (mean \pm SD age 8.3 ± 1.1 y, 47 girls, BMI z-score 2.7 ± 0.7). A subgroup of obese participants ($n = 35$; $2.5 < \text{BMI z-score} < 3.5$) was also compared to the total cohort to minimise the effects of variations in BMI. Plantar pressure distributions were quantified as participants walked over an emed[®] AT-4 pressure system and accelerometry was used to measure physical activity.

Results: Peak pressures generated beneath the forefoot were significantly and inversely correlated with time spent in different intensity levels of physical activity. Moderate ($r = -0.321, p = 0.007$), vigorous ($r = -0.326, p = 0.006$) and moderate-to-vigorous ($r = -0.342, p = 0.004$) intensity physical activity all correlated with middle forefoot pressure and with lateral forefoot pressure ($r = -0.248, p = 0.040$; $r = -0.264, p = 0.028$; $r = -0.267, p = 0.027$, respectively). Lateral midfoot ($r = -0.244, p = 0.044$) and second toe

($r = 0.227$, $p = 0.021$) pressure also correlated with vigorous intensity activity.

Conclusion: Those overweight/obese children who generated greater pressures beneath their forefoot and midfoot had lower levels of physical activity. Although statistically significant, the correlations were low warranting further research to determine whether long-term excessive body mass affects participation in physical activity due to foot discomfort.

Introduction

The benefits of physical activity in childhood and adolescence have been well documented (1). For children, regular physical activity has the additional benefit of promoting musculoskeletal growth and motor skill development, which can foster immediate and long-term participation in physical activity (2).

Despite the established physiological and psychological benefits of participating in physical activity, a high proportion of children are insufficiently active (3,4). One of the potential consequences of being inactive during childhood is the risk of becoming overweight or obese (5,6). The need of overweight and obese individuals to bear excess body mass can, in turn, cause musculoskeletal pain and discomfort, perpetuating the cycle of obesity due to inadequate activity levels associated with this discomfort (7,8). Even performing the fundamental activity of walking may be limited by high levels of obesity (9,10).

It has been postulated that the high pressures generated beneath the feet of obese adults during walking can cause lower extremity pain and discomfort and may result in musculoskeletal degeneration (11,12), which can be severe enough to reduce the level of physical activity of obese individuals (12). However, the effect of high plantar pressures upon the feet of children is less well known. As obese children generate

significantly higher dynamic peak pressures beneath their feet compared to normal-weight children of a similar age (13,14), we and others have suggested that these high pressures may be associated with the amount and type of physical activity obese children participate in (10,13,14). However, no published research has investigated whether higher plantar pressures are related to physical activity levels in overweight or obese school-aged children. Therefore, the aim of the present study was to establish whether the peak plantar pressures generated during walking by overweight and obese children were related to their objectively-measured physical activity.

Methods

Participants

Seventy three overweight and obese children (47 girls, 26 boys) participated in this study and were recruited as a subsample from a cohort who had volunteered to participate in an obesity treatment trial (15). Baseline data were used for the current analysis. The recruitment process (explained in detail elsewhere; 15) included telephone communication with, and information sent to, local schools, general practitioners and hospital clinics, and posters placed in public areas. Media releases were organised by the University of Wollongong Media Unit and resulted in advertisements in local newspapers, radio broadcasts and television coverage encouraging interested families to contact the research team. Children were between 5.5 and 9 years of age, generally healthy, prepubertal and overweight/obese (16). Extreme obesity, syndromal causes of obesity, long term steroid use, weight gain due to medication use, chronic illness and significant dietary restrictions comprised the exclusion criteria (15). The University of Wollongong Human Research Ethics Committee approved study procedures [HE05/010]; parents gave written, informed

consent for their children to participate and children gave verbal consent. All measurements were collected at the University of Wollongong, Australia.

Anthropometry

Body mass was measured to the nearest 0.01 kg using a set of Tanita HD464 scales (Tanita Corporation of America Inc, Illinois, USA). Standing height was measured to the nearest 0.1 cm using a PE87 portable stadiometer (Mentone Educational Centre, Victoria, Australia). Two recordings of each measurement were taken with participants bare foot and wearing lightweight clothing. The mean of the two measurements were used to calculate body mass index (BMI) z-score (17; using reference data from the United Kingdom).

Plantar Pressure Distribution

Dynamic plantar pressure distributions generated underneath each child's feet were quantified as the children walked over a calibrated emed® AT-4 pressure system (Novel_{gmbh}, Munich, Germany). The platform was embedded flush into a walkway and participants contacted this platform with their second step (18) while accompanied by an assistant walker. To ensure normal walking and to avoid targeting of the platform, familiarisation trials were performed before data were collected for three successful trials for each participant's left and right foot.

Resultant pressure footprints were divided into 10 regions (Figure 1; 19) and masked using Novel-ortho automask software (Novel_{gmbh}, Munich, Germany: Version 13.3.16, see Figure 1). The mean peak pressure footprints were then analysed using Novel-win multimask software (Novel_{gmbh}, Munich, Germany: Version 13.3.16) to determine the maximum contact area (cm²), maximum force (N), and peak pressure (kPa) in each of the masked areas of the plantar surface of the foot.

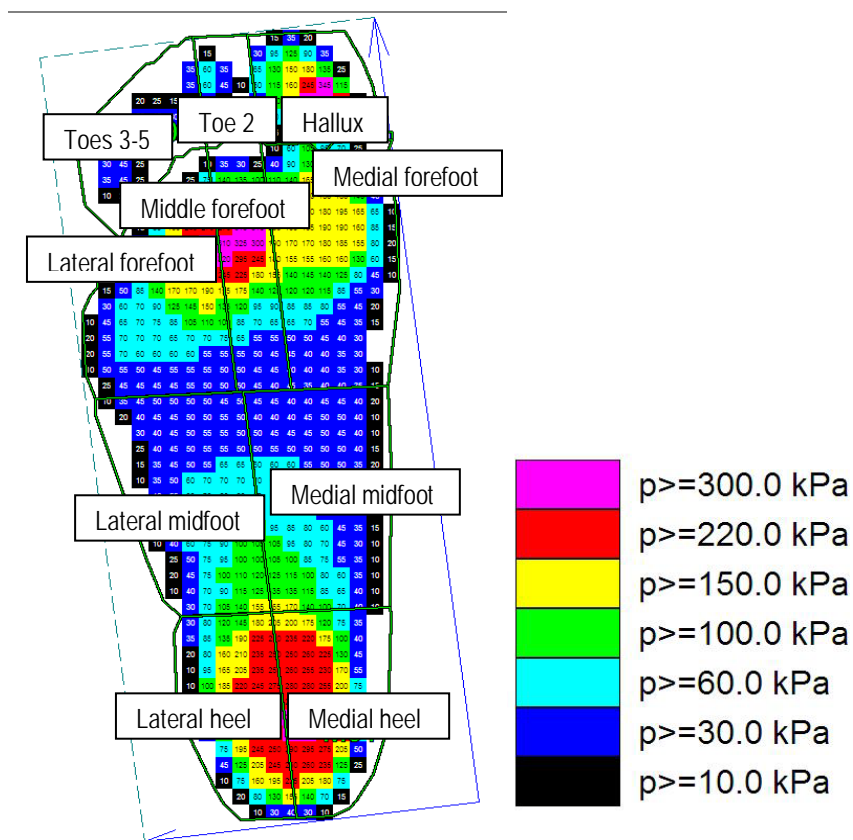


Figure 1. An example of a mean peak pressure distribution image of the left foot indicating the masked regions and the corresponding pressure values (kPa) generated in each sensor. [$p \geq$ depicts the level at which the pressure is greater than or equal to].

Physical Activity

Each participant was fitted with an Actigraph 7164 accelerometer (Actigraph, Florida, USA) as previously described (20), which was secured over their right hip. The accelerometer was worn over an 8-day period during all waking hours (excluding aquatic activities) and data were collected in 60 second epochs. When a sequence of greater than 20 consecutive '0' counts occurred, it was interpreted as non-wear time and not included in analyses. Participant data were included in analyses if accelerometers were worn for ≥ 10 hours per day on ≥ 4 days. Mean activity counts per minute (CPM) of monitoring time were calculated and used in analyses as a measure of total physical

activity. Additionally, activity count thresholds were applied to the data using an age-specific energy expenditure prediction equation to calculate time spent in moderate (MPA; 3.0–5.9 metabolic equivalent units of rest [METs]), vigorous (VPA; > 6.0 METs) and moderate-to-vigorous (MVPA; > 3.0 METs) physical activity (21). To adjust for variations in wear time, the percentage of time children were involved in MPA, VPA and MVPA were calculated (for a more detailed explanation see 20,22).

Statistical Analyses

Initial analysis of the pressure data produced few significant differences between the children's left and right feet. Therefore, as there was a complete data set for the left feet of all the participants, data for this foot were selected for statistical analysis. Pearson product moment correlation coefficients were calculated to determine the strength of the relationships (significant at $p < 0.05$) between the primary outcome variables of BMI, peak plantar pressures and physical activity for the total cohort of participants. In an attempt to control for any interaction of plantar pressure with weight status on physical activity, the cohort was then subdivided into an obese subgroup with similar BMI values: $2.5 < \text{BMI z-score} < 3.5$ and the correlation coefficients recalculated. Data for the overweight ($1 < \text{BMI z-score} < 2$), lower range obese ($2 < \text{BMI z-score} < 2.5$) and upper range obese ($3.5 < \text{BMI z-score} < 4$; 17) participants were discarded from this analysis to minimise the effects of variations in BMI values on the correlation coefficients. BMI z-score was used to adjust for age. All statistical analyses were conducted using SPSS software (SPSS 17 for Windows, Illinois, USA).

Results

Descriptive characteristics and mean (\pm SD) scores for physical activity outcomes are presented in Table 1. Figure 2 displays plantar pressure distributions

generated by the participants during walking. All correlation coefficients calculated between the test variables are shown in Tables 2 and 3. For the total sample, there was no association between peak plantar pressures generated beneath the feet during walking and total physical activity Table 2).

Table 1. Sample characteristics and physical activity (mean \pm SD) for the obese subgroup and the total cohort.

Variable	Obese Subgroup (n = 35)	Total (n = 73)
Age (y)	8.4 \pm 1.1	8.3 \pm 1.1
BMI (kg/m ²)	25.6 \pm 2.7	24.7 \pm 3.7
BMI z-score	2.9 \pm 0.3	2.7 \pm 0.7
Mass (kg)	49.2 \pm 9.8	46.5 \pm 11
Height (m)	1.38 \pm 0.09	1.37 \pm 0.09
Total PA (mCPM)	618.2 \pm 153.7	652.1 \pm 166.8
Moderate PA (%)	20.1 \pm 6.4	20.6 \pm 6.2
Vigorous PA (%)	2.7 \pm 1.7	3.0 \pm 1.9
Moderate-Vigorous PA (%)	22.8 \pm 7.6	23.6 \pm 7.6

PA = physical activity; mCPM = mean counts per minute, % = percent monitored time per day

Table 2. Pearson product moment correlation coefficients between peak plantar pressures and total physical activity (counts per minute) for the obese subgroup and the total cohort.

Foot Region	Obese Subgroup (n = 35)	Total (n = 73)
Medial heel	.092	.102
Lateral heel	.081	.075
Medial midfoot	-.181	-.041
Lateral midfoot	-.277	-.124
Medial forefoot	.233	.057
Middle forefoot	-.009	-.224
Lateral forefoot	-.087	-.188
Hallux	.221	-.133
Toes 2	.281	.213
Toes 3-5	.050	-.013

** indicates a significant correlation (p < 0.05)*

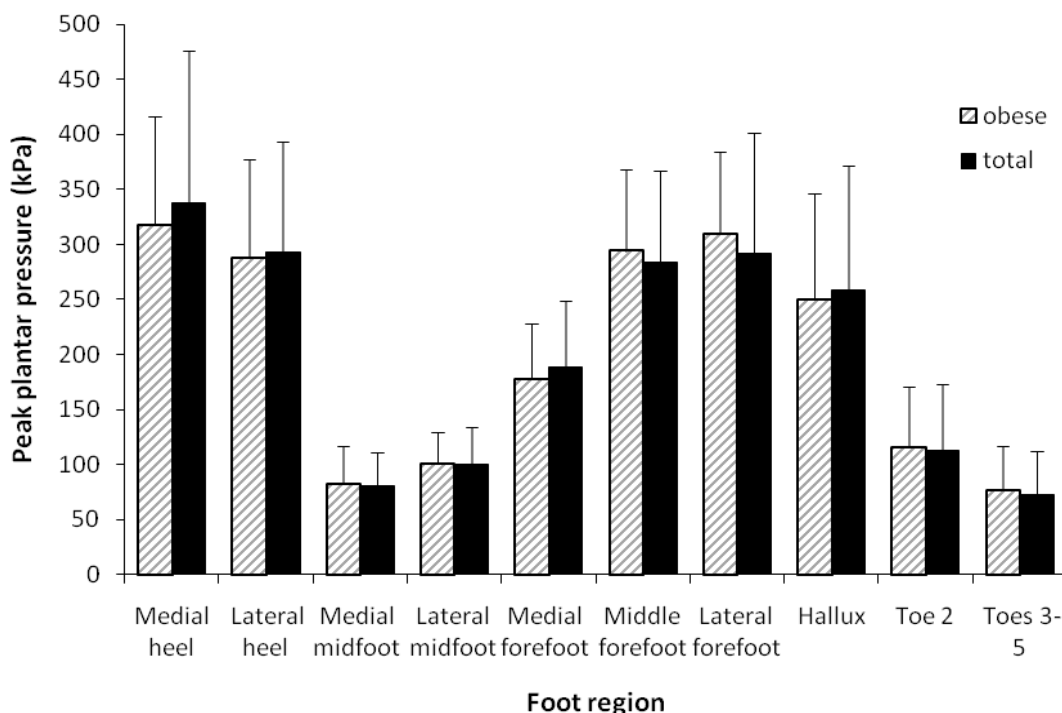


Figure 2. Peak plantar pressure distributions (kPa; mean \pm SD) generated when walking by the obese subgroup (n = 35) and the total cohort (n = 73).

Table 3. Pearson product moment correlation coefficients between peak plantar pressures and time in MPA, VPA and MVPA for the obese subgroup and the total cohort.

Foot region	Obese Subgroup (n = 35)			Total (n = 73)		
	MPA	VPA	MVPA	MPA	VPA	MVPA
Medial heel	.038	-.001	.032	-.002	.018	.003
Lateral heel	.063	.005	.054	-.032	.003	-.025
Medial midfoot	-.053	-.161	.009	.013	-.053	-.002
Lateral midfoot	-.052	-.375*	-.127	-.095	-.244*	-.137
Medial forefoot	.055	.118	-.073	-.078	-.062	-.079
Middle forefoot	-.281	-.076	-.254	-.321*	-.326*	-.342*
Lateral forefoot	-.213	-.248	-.234	-.248*	-.264*	-.267*
Hallux	.278	.173	.237	.057	-.074	.028
Toes 2	.128	.286	.171	.110	.277*	.157
Toes 3-5	-.066	.020	-.051	-.027	.088	-.001

MPA = moderate physical activity, VPA = vigorous physical activity, MVPA = moderate-to-vigorous physical activity

* indicates a significant correlation ($p < 0.05$)

Higher peak plantar pressure distributions beneath the middle and lateral forefoot for the total group were significantly and inversely related to a lower percentage of time spent in MPA ($p = 0.007$ and $p = 0.040$), VPA ($p = 0.006$ and $p = 0.028$) and MVPA ($p = 0.004$ and $p = 0.027$), respectively (Table 3). There was also a significant inverse association between pressure generated beneath the lateral midfoot and VPA ($p = 0.044$) for the total group. Pressure distribution beneath the second toe was significantly and positively associated with the percentage of time the children spent in VPA ($p = 0.021$). In the obese subgroup, only pressure beneath the lateral midfoot was significantly and inversely associated with VPA ($p = 0.029$), although this subgroup of participants displayed similar trends to the total cohort for the association of MPA, VPA and MVPA with the forefoot plantar pressures.

Discussion

This study aimed to investigate whether the peak plantar pressures generated by overweight and obese children during walking were significantly related to their objectively-measured physical activity. We found higher plantar pressures were inversely associated with children's moderate and vigorous intensity physical activity.

In the present study of school-aged overweight and obese children, higher plantar pressures in the middle and lateral forefoot were associated with lower levels of MPA, VPA and MVPA. Among the obese subgroup with homogenous BMI values, the same trends were evident with respect to higher plantar pressures in the middle forefoot and decreased time spent in MPA and MVPA and higher lateral forefoot pressure with time in VPA, although the associations were no longer significant. The significant finding for the total sample, but not the homogeneous obese subgroup, was mainly due to the lower participant numbers in the obese subgroup, as the strength of the correlation

coefficients was extremely similar (Table 2 and 3). Participation in vigorous physical activity was also inversely associated with higher lateral midfoot pressure. As the subgroup of obese participants also displayed significantly greater lateral midfoot pressures with reduced VPA, it is speculated that higher pressure beneath this foot region may contribute to a reduction in participation in vigorous types of weight-bearing activity for obese children.

The percentage of time spent in VPA for the total cohort increased as pressure distribution beneath the second toe increased. This finding was in contrast to a study of younger, predominantly non-overweight, children in which an increase in sedentary behaviour was associated with greater pressures beneath toes 2 to 5 combined (13). Our overweight and obese participants may have transferred pressure away from the hallux and forefoot to the second toe during vigorous activity. The trend for the obese subgroup to display a similar result to the total cohort was again apparent for this foot region.

Although the appearance of prepubertal children's feet resembles that of adult feet, children's feet continue to develop reaching maturing later in the second decade of life. It has been postulated that higher plantar pressures associated with continually bearing excess mass on their developing feet may lead to foot pain and foot dysfunction in overweight and obese children (23). Whereas this notion has not been investigated systematically in children, foot pain in adults has been significantly correlated with elevated plantar pressures during walking. Higher plantar pressures generated beneath the middle forefoot of patients with degenerative disorders (24) and higher total peak pressures and pressure-time integrals generated beneath the feet of older adults from a community sample (25) have also been associated with increased pain levels. Furthermore, higher plantar pressures during walking in obese adults predispose these

individuals to foot pain and have implications for participating in physical activity (11). For example, Hitt et al. (26) reported lower physical activity levels among obese adults as a result of pain and discomfort in their lower limbs, whereas weight-loss in obese adults resulted in a reduction in foot pain and an increase in physical activity (27). The one paediatric study to investigate the relationship between plantar pressure and objectively-measured physical activity was a study of preschool-aged children (13), which found that higher plantar pressures were inversely correlated with MVPA, and total physical activity, and were associated with increased sedentary behaviour in children less than 5 years of age (13). Low physical activity levels have also been associated with children who experience pain and discomfort during activity (8,10). The feet of the overweight and obese children we investigated therefore appear to be at risk of potential foot problems if these children are continually involved in weight-bearing activities in an attempt to achieve the recommended levels of MVPA that would facilitate reductions in unhealthy weight gain (5). If this notion is correct and excessive body mass is resulting in foot discomfort when participating in weight-bearing physical activity, it may be necessary to encourage these children to participate in non-weight-bearing physical activity, such as cycling or aquatic-based activities, in an attempt to reduce potential foot pain, discomfort or dysfunction.

Although the results of this study suggest that less physically active overweight and obese children experienced greater pressures beneath their forefoot and midfoot regions, it is acknowledged that these correlation values, although significant, were low (strong correlation values approach -1 or +1, moderate values between -0.5 to -0.8 and +0.5 to +0.8, with weak or low values between -0.5 and +0.5; 28). In fact, only 6% to 12% of the value in the outcome variables could be accounted for by their relationship with the peak plantar pressure data and many of these significant correlations were only

a non-significant trend when data for the homogenous BMI-group of obese children were analysed. Nevertheless, children need to be more physically active (29). However, if overweight and obese children are at risk of foot discomfort or pain from higher plantar pressures during physical activity, they are likely to be reluctant to participate. The results of this study therefore highlight that further research is warranted to investigate how long-term excessive body mass affects foot discomfort and plantar pressures generated during physical activity, and in turn, how these factors influence overweight and obese children's participation in physical activity. Results of such studies can inform interventions designed to encourage overweight and obese children to increase their participation in moderate-to-vigorous physical activity.

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Chapter 6

Plantar pressures and foot structure:

Are these factors moderated by a physical activity program in overweight and obese children?

This chapter is an amended version of the manuscript: Riddiford-Harland DL, Steele JR, Cliff DP, Okely AD, Morgan PJ, Jones RA, Baur LA. Plantar pressures and foot structure: Are these factors moderated by an activity program in overweight and obese children? *International Journal of Obesity*. Submitted for publication 16 December, 2010.

Abstract

Objective: To investigate the effects of a weight-bearing physical activity (PA) program on foot structure and plantar pressures generated by overweight and obese children.

Methods: Measurements were collected at baseline and 6-months for a convenience subsample of children participating in an obesity treatment trial (mean \pm SD 8.5 ± 1.1 y, 29.4 % boys, 2.63 ± 0.61 BMI z-score). Data for 24 children randomized to a physical activity program (PA) and 10 children randomized to no physical activity program (NPA) were analysed. Foot structure was characterised using anthropometric measures, dynamic plantar pressure distributions were quantified using an emed® AT-4 pressure system and accelerometers worn for ≥ 10 hours/day on ≥ 4 days assessed physical activity.

Results: After 6 months there was a significant decrease in BMI z-score (PA: $p = 0.002$, NPA: $p < 0.001$), and an increase in foot length (PA: $p < 0.001$, NPA: $p < 0.001$) and

foot height (PA: $p < 0.001$, NPA: $p = 0.008$) for the total cohort, although there was no change in physical activity for either group. Pressure-time integrals generated during gait increased for both groups after 6 months (lateral midfoot; PA: $p = 0.036$, medial forefoot; PA: $p = 0.002$, NPA: $p = 0.013$, middle forefoot; PA: $p = 0.044$, lateral forefoot; PA: $p = 0.043$) but there were no between-group differences in plantar pressures as a result of participating in the physical activity program.

Conclusion: Although changes to foot structure and function of overweight and obese children could not be attributed to participating in the physical activity program, their developing feet may still be at risk of pain and discomfort due to higher plantar pressures. Further research investigating ways to reduce plantar pressures generated by overweight and obese children while they are physically active are therefore warranted.

Introduction

Physical inactivity has been identified as a major factor contributing to the development of overweight and obesity in children (1). One specific barrier thought to restrict overweight and obese children from being physically active is the musculoskeletal consequences these children experience due to carrying excess weight (2,3). For example, overweight and obese children have fatter and flatter feet (4,5) and generate higher pressures beneath the midfoot and forefoot regions when compared to their non-overweight peers (6,7). This flattening of the medial longitudinal arch of the foot and higher plantar pressures are thought to be a cause of foot discomfort, pain or dysfunction and, consequently, a possible deterrent to activity in obese children (6-8). In support of this notion, we recently showed, in overweight and obese school-aged children, that higher peak plantar pressures generated during walking were significantly associated with lower levels of physical activity (9).

Increasing physical activity is one recommended approach to combating the high prevalence of obesity among children (1,10). However, there has been no systematic investigation of the types of activity in which obese children should participate and how this choice affects plantar pressure distributions and foot development. Although a 5-week weight-loss program successfully reduced body mass and peak plantar pressures generated by obese adolescents (11), this study did not clarify what movement activities participants were required to perform during the program. Furthermore, no published literature was located examining the consequences of increasing weight-bearing physical activity during an intervention program on peak pressures generated beneath the feet of overweight and obese children.

Therefore the purpose of the present study was to examine the effects of a weight-bearing physical activity program on foot structure and plantar pressures generated by young overweight and obese children. We hypothesised that participation in a weight-bearing physical activity program aimed at increasing physical activity level would result in higher pressure distributions beneath the feet of overweight and obese school-aged children compared to those children who are not involved in a physical activity intervention.

Methods

Participants

Participants were recruited as a convenience subsample of a child obesity treatment trial known as the Hunter and Illawarra Kids Challenge using Parent Support (HIKCUPS; described in detail elsewhere; 12). Participant inclusion criteria for HIKCUPS were children aged between 5 and 9 years who were generally healthy, prepubertal and overweight or obese according to International Obesity Task Force cut

points (13). Extreme obesity (BMI z -score >4), known syndromal causes of obesity, long-term steroid usage, weight gain due to medication, chronic illness and significant dietary restrictions comprised the exclusion criteria (12).

Overall HIKCUPS Study Design

Participants for HIKCUPS were randomized into one of three groups; a child-centred physical activity program, a combined child-centred physical activity and parent-centred dietary modification program, or a parent-centred dietary modification program (12) and baseline measurements were collected. Children randomly assigned to the physical activity and combined intervention groups then followed a 10-week 90 minute face-to-face physical activity program, which commenced 2 weeks after collecting baseline data. The program was followed by a 3-month maintenance period whereby contact was maintained with these children via telephone calls to their families at 14, 18, and 22 weeks after face-to-face session commencement. A 2-hour physical activity booster session was conducted 2 months after the last face-to-face session to support motivation and skill development during the maintenance (12). Parents of children randomly assigned to the combined intervention and the dietary intervention were involved in a family-focused dietary modification program during this time (14). The children who were randomly assigned to the parent-centred dietary modification program received treatment that did not involve or promote physical activity. Six months after baseline data collection (post intervention) all groups were again assessed on all study variables. Researchers were blinded to group allocation during data collection and analysis.

Selection of the Convenience Subsample

For the present study, participants in the Wollongong cohort of the HIKCUPS study were approached to collect foot anthropometry and plantar pressure distribution data,

which were additional variables to those being assessed in the HIKCUPS study (12). Consenting participants who had complete foot anthropometry and plantar pressure distribution datasets for both the baseline and 6-month testing sessions and participated in the physical activity program comprised the physical activity treatment group (n = 24; Physical Activity [PA]). Children who had complete datasets but did not participate in the physical activity program formed the activity placebo group (n = 10; No Physical Activity [NPA]). The process for data collection for the convenience subsample of the present study is represented in Figure 1. Parents gave written, informed consent and children gave verbal consent to participate. Data for this subsample were collected at the University of Wollongong, Australia, and the University of Wollongong Human Research Ethics Committee [HE05/010] approved all study procedures.

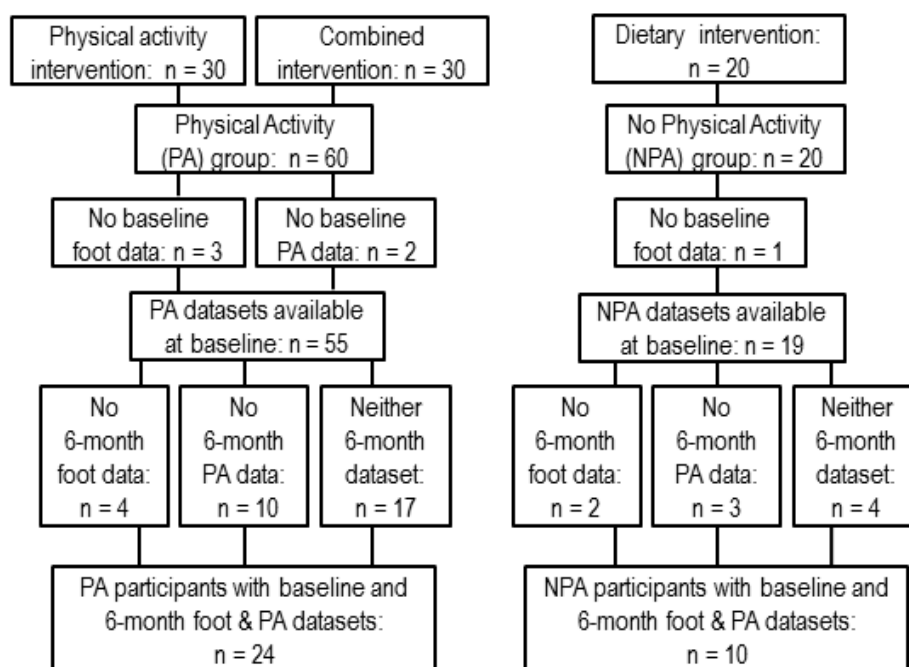


Figure 1. A schematic representation of all participants who entered the Wollongong cohort of the HIKCUPS study and which participants had both foot data and physical activity data at baseline and 6-months to comprise the convenience subsample for this study.

Physical Activity Program

During the 10-week face-to-face physical activity program participating children completed weight-bearing physical activity tasks aimed at improving their actual competence in performing 12 fundamental movement skills (run, jump, leap, hop, slide gallop, and strike, roll, kick, throw, catch, and bounce a ball) and their perceived competence in physical activity and sports (15). Tasks were designed to cater for the participant's differing stages of learning and development and were tailored to detect and correct errors in skill performance to allow for the provision of skill-specific feedback. Consecutive sessions concentrated on three fundamental movement skills with more complex skill components introduced and revisited through the latter part of the program.

In addition to face-to-face sessions, children were provided with 'home challenges' to encourage the practice of fundamental movement skill tasks with family members or friends between sessions. These at-home sessions were designed to facilitate participation, improve competency and promote physical activity. A minimum of 30 min of at-home participation, three times each week, during the 10-week physical activity program was recommended (see 15; for detailed explanation of the physical activity program).

Anthropometry

Tanita HD464 scales (Tanita Corporation of America Inc, Illinois, USA) were used to measure participants' body mass to the nearest 0.01 kg. A PE87 portable stadiometer (Mentone Educational Centre, Victoria, Australia), accurate to 0.1 cm, was used to measure standing height. The mean of two measurements (within 0.03 kg or within 3 mm) were used to calculate body mass index (BMI; weight (kg)/height (m)²).

Age- and sex- adjusted BMI z-scores were then computed using UK reference values (16). Participants were barefoot and wore light-weight clothing during data collection.

Plantar Pressure Distribution

The dynamic plantar pressure distributions generated underneath each child's feet were measured as they walked at a prescribed pace across a calibrated emed® AT-4 pressure system (Novel_{gmbh}, Munich, Germany), which was embedded in a 3 m walkway. Data were collected as the participant contacted the platform with their second step as this method has been suggested to produce a good representation of gait in children (17). Participants were accompanied by an assistant to ensure they maintained a standardised walking pace and to avoid targeting of the platform. Familiarisation trials were performed before data were collected for three successful trials for each foot.

Each pressure footprint was divided into 10 regions (medial and lateral heel; medial and lateral midfoot; medial, middle and lateral forefoot; big toe; second toe; and 3rd-5th toes; 18). These regions of the footprint were masked using Novel-ortho automask software (Novel_{gmbh}, Munich, Version 13.3.16). For each of these masks, Novel-win multimask software (Novel_{gmbh}, Munich, Version 13.3.16) was used to analyse the mean peak pressure footprints to determine the maximum contact area (cm²), maximum force (N), peak pressure (kPa) and pressure-time integrals (kPa/s) generated during the gait cycle. Only medial and lateral midfoot and medial, middle and lateral forefoot peak pressure and pressure-time integral values have been included in the results section due to previous studies identifying these foot regions being at potential risk for overweight and obese children during exercise (6,9).

Foot Anthropometry

Foot length, ball of foot length, instep length, ball of foot breadth, heel breadth, ball of foot height, dorsal arch height, plantar arch height, ball of foot circumference and instep circumference were measured for both feet of each participant to the nearest millimetre. All anthropometric foot measurements (19) were recorded by the chief investigator [DLRH] using a combination level (Stanley Tools, Connecticut, USA), a metal tape (KDS Corp., Kyoto, Japan), small anthropometer (Lafayette Instrument Co., Indiana, USA) and a custom-designed foot tray. Two measurements (within 3 mm) were taken while participants stood barefoot with equal weight on both feet. The mean per variable was used in later analysis to represent each foot dimension.

A portable SonoSite® 180PLUS ultrasound system (Washington, USA) with a 38 mm broadband linear array transducer (10-5 MHz, 7 cm maximum depth) was used to quantify internal medial longitudinal arch (internal arch; mm) height of each child's right and left foot. To standardise internal arch height assessment, the ultrasound probe was held in a cut-out section of a Perspex platform onto which the participant stood. The transducer was placed longitudinally and vertically below the dorsal navicular landmark and aligned with the second metatarsal (4). The distance from the supporting surface of the platform to the joint beneath the dorsal navicular landmark was quantified to 0.01 cm. Three trials were collected with the mean value representative of left and right internal arch height (for a more detailed explanation see 4). The chief investigator [DLRH] took all measurements to maximise reliability.

Physical Activity Measurement

Participants were fitted with an Actigraph 7164 accelerometer (Actigraph, Florida, USA) as previously described (15). The accelerometer was secured over their right hip and worn for an 8-day period during all waking hours (excluding aquatic

activities) and data were collected in 60 second epochs. During data reduction, sequences of ≥ 20 consecutive '0' counts were interpreted as non-wear time and excluded. Participant data were included in the analyses if accelerometers were worn for ≥ 10 hours per day on ≥ 4 days. Mean activity counts per minute (CPM) of monitoring time were calculated and used as a measure of total physical activity. Additionally, activity count thresholds were applied to data using an age-specific energy expenditure prediction equation to calculate time spent in moderate (MPA; 3.0–5.9 metabolic equivalent units of rest [METs]), vigorous (VPA; > 6.0 METs) and moderate-to-vigorous (MVPA; > 3.0 METs) physical activity (20). The percentage of time children were involved in MPA, VPA and MVPA was calculated to adjust for variations in wear time (for a more detailed explanation see 15,21).

Statistical Analyses

Initial analysis of the foot anthropometric and pressure data produced few differences between the children's left and right feet. As there was a complete data set for all participants' left feet, data for this foot were selected as representative of each child's foot function and were included in the statistical analysis. The Kolmogorov-Smirnov test (with Lilliefors' correction) and Leven median test were used to assess normality and equal variance, respectively. The intervention effect on all outcome variables after 6 months was assessed via a repeated measures analysis of variance, with paired (time effects) and independent (group effect) *t*-tests used for *post hoc* analysis. All statistical analyses were conducted using SPSS software (SPSS 17 for Windows, Illinois, USA).

Results

There were no significant between-group differences for any of the outcome variables at baseline (with the exception of internal arch height, $p < 0.007$; Table 1). A significant increase in standing height combined with no change in body mass for either group after 6 months resulted in a significant decrease in BMI z-score for the PA group ($p = 0.001$) and the NPA group ($p < 0.002$; Table 1). All foot length measures, internal arch height and dorsal arch height significantly increased after 6 months for both participant groups (Table 1), whereas ball-of-foot height, plantar arch height, and foot breadth and circumference measures remained stable. There were no between-group differences in foot anthropometry post intervention at 6 months.

Table 1. Descriptive characteristics, foot anthropometry and total physical activity at baseline and 6-months post baseline (mean \pm SD) for the Physical Activity (PA) and No Physical Activity (NPA) groups.

Variable	PA (n = 24)		NPA (n = 10)	
	Baseline	6 months	Baseline	6 months
Age (y)	8.5 (1.1)	8.9 (1.1)*	8.4 (1.4)	8.8 (1.4)*
Mass (kg)	46.4 (12.8)	47.3 (13.8)	46.0 (9.0)	45.6 (9.5)
Height (m)	1.37 (0.10)	1.40 (0.11)*	1.39 (0.11)	1.42 (0.11)*
BMI z-score	2.62 (0.60)	2.36 (0.61)*	2.65 (0.68)	2.22 (0.67)*
Internal Arch Height (mm)	23.2 (1.3)#	24.0 (1.3)*	21.8 (1.1)	23.1 (0.8)*
Foot Length (mm)	216 (17)	222 (16)*	215 (21)	221 (20)*
Ball of Foot Length (mm)	157 (13)	163 (12)*	157 (15)	161 (17)*
Instep Length (mm)	105 (14)	119 (11)*	108 (15)	120 (15)*
Ball of Foot Breadth (mm)	84 (9)	86 (7)	86 (7)	86 (7)
Heel Breadth (mm)	57 (4)	57 (4)	55 (5)	54 (4)
Dorsal Arch Height (mm)	63 (6)	66 (5)*	61 (5)	64 (6)*
Ball of Foot Height (mm)	35 (4)	34 (3)	35 (3)	34 (3)
Plantar Arch Height (mm)	14 (4)	15 (3)	14 (2)	15 (4)
Instep Circumference (mm)	215 (15)	213 (16)	213 (15)	212 (16)
Ball of Foot Circumference (mm)	215 (15)	217 (15)	213 (14)	216 (17)
Total Physical Activity (CPM)	646 (157)	682 (175)	654 (246)	600 (192)

* indicates a significant within-group difference ($p < 0.05$)

indicates a significant between-group difference ($p < 0.05$)

There was no effect of time or participant group on MPA, VPA or MVPA (Figure 2) such that involvement in the physical activity intervention did not change the percentage of time these children participated in physical activity after 6 months. Total physical activity (CPM; Table 1) also remained stable after 6 months with no significant difference between groups before or after the physical activity intervention.

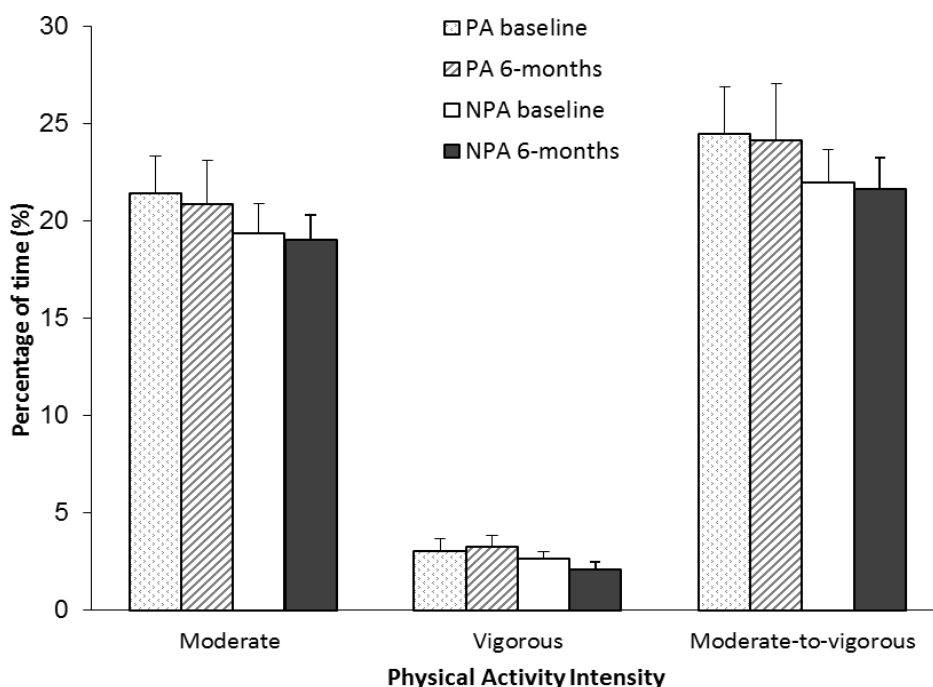


Figure 2. Mean (\pm SD) percent time spent in MPA, VPA and MVPA at baseline and 6-months post baseline for the Physical Activity (PA) and No Physical Activity (NPA) groups.

The magnitude of the peak plantar pressure distributions generated during walking was not altered via participation in the weight-bearing physical activity program (Figure 3). However, there was a significant difference in the pressure-time integrals generated beneath the forefoot for both groups post intervention. For the PA

group, there was a significant increase in the pressure-time integral under the lateral midfoot ($p = 0.036$) and medial ($p = 0.002$), middle ($p = 0.044$) and lateral forefoot ($p = 0.043$) from baseline to 6-months. In contrast, the medial forefoot was the only foot region to display a significantly increased pressure-time integral after 6 months for the NPA group ($p = 0.005$; Figure 4). There were no between-group differences in pressure-time integrals after the 6-month intervention.

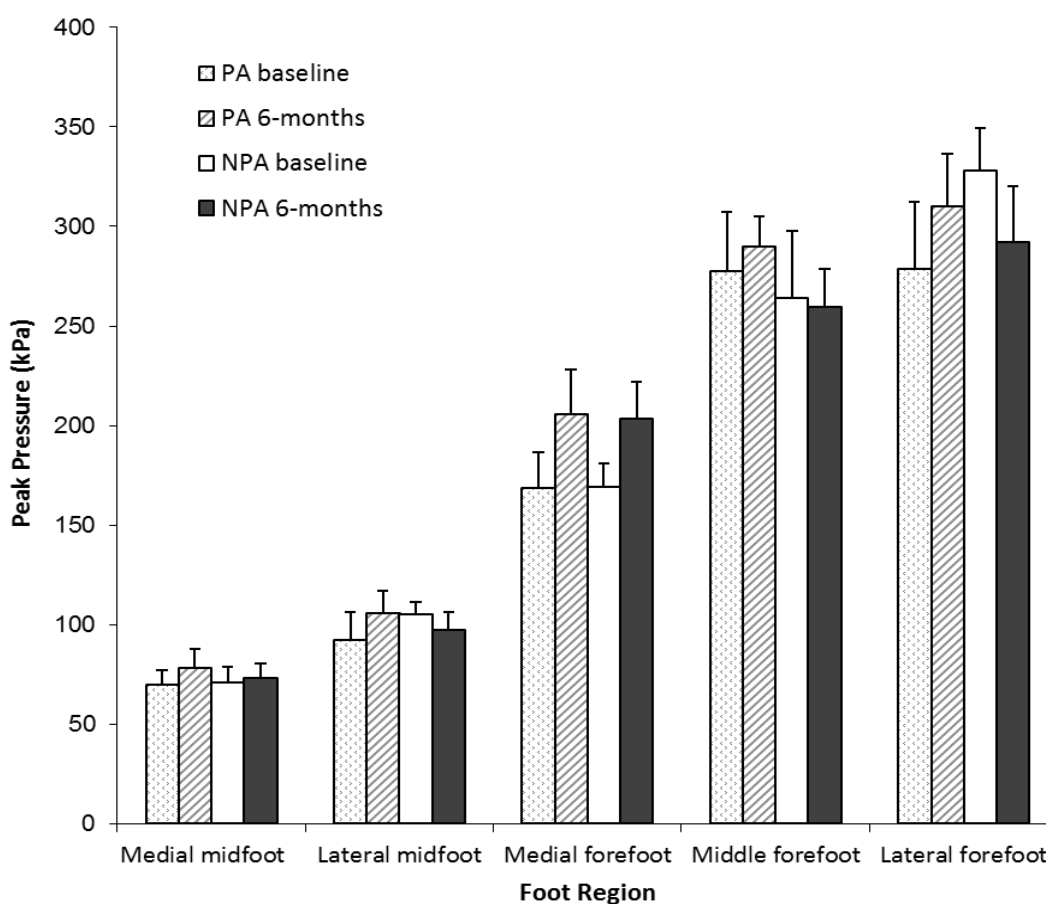


Figure 3. Means (\pm SEM) peak plantar pressure at baseline and 6-months post baseline for the Physical Activity (PA) and No Physical Activity (NPA) groups.

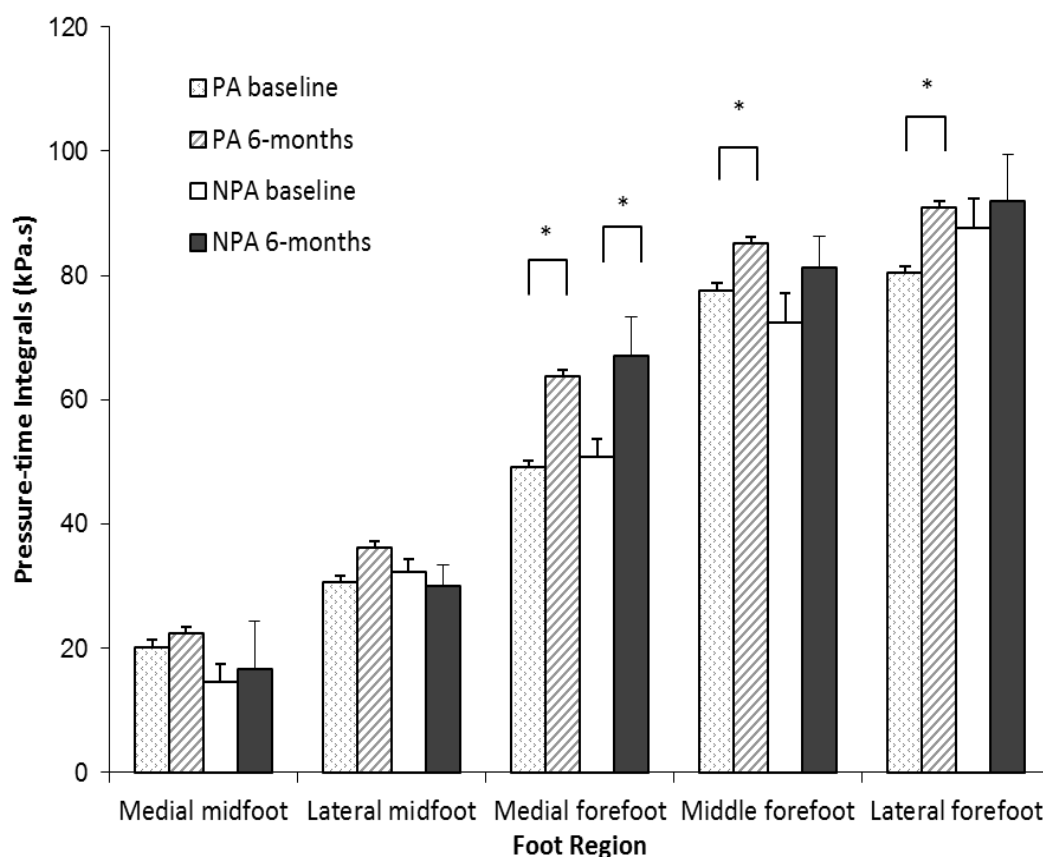


Figure 4. Mean (\pm SEM) pressure-time integrals at baseline and 6-months post baseline for the Physical Activity (PA) and No Physical Activity (NPA) groups (* indicates a significant within-groups difference, $p < 0.05$).

Discussion

Increased physical activity among overweight and obese children is considered central to prevention of unhealthy weight (1). The possibility, however, of higher plantar pressures and structural changes exacerbating foot pain and discomfort during participation in weight-bearing physical activity interventions seems reasonable, although this idea has not been investigated systematically. The present study is the first to reveal that overweight and obese children who participated in a physical activity program that stabilised their body mass, avoided increases in plantar pressures after a 6-

month period. However, as pressure-time integrals increased these overweight and obese children's feet remain at risk of possible foot pain and discomfort.

As anticipated due to normal growth, the children's foot length, internal arch height and dorsal arch height significantly increased during the 6 months for both participant groups. The only between-group difference at baseline was internal arch height, indicating that the PA group had, on average, a higher arched foot compared to the NPA group. However, this difference was no longer apparent 6-months after baseline as both groups recorded a similar arch height. As all other foot measures remained stable at 6-months relative to baseline, maintaining the BMI z-score of participants appears to have stabilised foot breadth, foot circumference and both ball-of-foot and external plantar arch height measures in this group of overweight and obese children; measures that are typically larger in obese children relative to their normal-weight peers (4).

There were no significant time x participant group interactions for any of the foot anthropometry measures, indicating that participating in the weight-bearing physical activity program did not affect the children's foot structure in a way that differed to changes associated with normal growth. Although the weight-bearing physical activity intervention was aimed at providing these participants with the necessary skills that should allow them to be more physically active, the program did not result in a significant increase in the amount of time these participants spent in physical activity after 6 months.

In contrast to our hypothesis, dynamic plantar pressure distribution post the physical activity program did not significantly increase in the PA group. Pressure distribution is calculated as force per unit area. The lack of change in pressure evident in this study may have been attributed to a maintenance in the forces that the children

generated during walking being distributed over a consistent foot-to-ground contact area (due to stable foot breadth dimensions with no subsequent change in midfoot or forefoot contact area after 6 months, despite increased foot length). We speculate that maintenance of body mass over the 6-month period avoided increases in the forces generated during gait and, in turn, the plantar pressures in this sample of overweight and obese young children.

Despite stable plantar pressures over the 6-month period, the pressure distribution patterns generated by the overweight and obese participants were higher when compared to normal weight children of similar age (7). Therefore, the potential for these children to develop foot pain or discomfort is still of concern, although the current intervention was successful in stabilising the children's body mass. As there is still no agreed threshold or range of plantar pressure values at which foot pain or discomfort negatively influences foot function, further research investigating this threshold and ways of reducing plantar pressures in overweight and obese children is warranted.

When the pressure-time integrals were compared between baseline and 6-months, there was a significant increase beneath the medial forefoot region for both groups. In a study of children aged between 6 and 10 years, a forefoot medial load shift away from the fifth metatarsal head to the first metatarsal head was evident with increasing age (22). A difference in the medial forefoot pressure-time integrals of participants in the present study may therefore have indicated growth and maturation to a more medially loaded foot. However, unlike the previous study (22), the lateral forefoot values in the present study significantly increased in the PA group and remained unchanged in the NPA group.

Although the PA group showed increased pressure-time integrals in a number of foot regions when compared to the NPA group at 6-months, limited participant numbers in the NPA group may have masked statistically significant findings and therefore these data should be interpreted cautiously. Comparison with normal-weight counterparts is also recommended to investigate the significant changes in pressure-time integrals displayed by the PA group because, although participants did not gain weight, their feet may still be at risk of pain and discomfort as higher pressure-time integrals have been associated with an increased risk of soft tissue damage (23,24). The clinical relevance of significant increases in pressure-time integral values in children, which ranged between 6.2 and 16.3 kPa.s after 6 months in the present study, should also be investigated with a comparative group of normal-weight school-aged children.

The findings were limited by an insignificant change in the amount of time children spent being physically active following participation in a physical activity intervention program. Therefore, we could not identify whether encouraging these still overweight and obese children to be more involved in weight-bearing activities resulted in a change in either peak pressure or pressure-time integral values. It should also be noted that follow-up assessment of these variables occurred 3 months after completion of the face-to face physical activity program such that immediate effects of the program on foot structure and function for this convenience subsample of overweight and obese children may not have been present after 6 months. This study did, however, result in a stabilisation of body mass and of the pressures these overweight and obese children generated beneath their feet. Nevertheless, plantar pressures remained high and pressure time integrals increased after a 6-month period warranting further investigation into ways to reduce these pressure distributions beneath the feet of overweight and obese children. Children should also be monitored for foot comfort throughout future

physical activity programs to better address the issues of potential pain, discomfort and/or dysfunction to their feet as a result of continually carrying extra body mass.

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Chapter 7

Summary, Conclusion and Recommendations for Further Research

Summary

The effect of excess body mass on the developing feet of overweight and obese children remains unclear. The primary aim of this thesis was therefore to systematically investigate the effects of obesity on foot structure and function of school-aged children through a series of studies in order to identify whether their feet were compromised as a result of carrying excess body mass. The first study aimed to design a reliable imaging technique, which would be used in subsequent studies of the thesis, to quantify medial midfoot fat pad thickness (Chapter 2) in young overweight and obese children. To achieve this aim, three methods to identify the joint between the inferior aspect of the navicular bone and the middle cuneiform bone, the reference site beneath which the fat pad thickness measurement would be taken, were tested. The three methods of locating this joint included: (i) placing the transducer directly below the joint, (ii) moving the transducer towards the joint, starting from the toes and (iii) moving the transducer towards the site starting from the calcaneus. As hypothesised, there was no statistically significant difference in the fat pad thickness measures using the three methods and interclass correlation coefficient values indicated all methods provided good reproducibility. There were also no differences in fat pad thickness measures between the left and right feet of the children for any of the three methods. As the direct placement method took the least amount of time, this method was selected for use in the subsequent studies because it was deemed more time efficient, an important consideration when collecting data from young children who are unlikely to remain

stationary throughout testing.

Using the imaging technique developed in Chapter 2, debate in the literature concerning whether broader footprints, evident in obese children, are indicative of structural lowering of the longitudinal arch (flat feet) or merely an increase in the amount of adipose tissue located in the medial midfoot (the medial midfoot fat pad; fat feet) was investigated. Body mass index (BMI) and foot anthropometry were recorded for 75 obese children and compared to values recorded for 75 age- and sex-matched non-obese children (Chapter 3). The results of Chapter 3 highlighted that obese children's feet were both flatter and fatter than the feet of their normal-weight counterparts and so could be at risk of developmental problems due to complications associated with lowered medial longitudinal arches. Based on these findings, Chapter 4 investigated the dynamic foot function of overweight and obese children as it related to medial midfoot fat pad thickness to determine whether the increased thickness of the medial midfoot fat pad (i.e. fatter feet) could provide protection for overweight and obese children's flatter feet during walking. Dynamic plantar pressure distributions beneath the feet of school-aged children (mean age = 8.1 years; n = 252) were correlated with medial midfoot fat pad thickness values and BMI. As hypothesised, BMI was significantly and positively correlated with both peak plantar pressures and medial midfoot fat pad thickness values. It was concluded that, due to the positive association also found between dynamic plantar pressures and fat pad thickness values, the fatter feet of overweight and obese children do not appear to compensate for the excess body mass they habitually carry. Having greater medial midfoot fat pad thickness did not provide protection against the higher pressures generated beneath the feet of overweight and obese children. However, what constitutes this fat padding in the medial midfoot, whether the histology of this fat padding relates to other fatty deposits

and whether its structural and functional properties change from infancy and throughout childhood, requires investigation to better understand its functional relevance to the developing foot.

Previous research has suggested that higher plantar pressures are a contributing factor to pain and discomfort experienced in the feet and lower limbs of individuals who are overweight or obese and may constitute a barrier to participation in physical activity. The higher pressures generated by the participants with a higher body mass identified in Chapter 4 may therefore predispose these children to foot pain or discomfort and influence their level of physical activity. Consequently, in Chapter 5 the relationship between pressure distributions generated beneath the feet during walking and during objectively-measured physical activity in overweight and obese children was examined. Accelerometers and an emed[®] AT-4 pressure system were used to measure physical activity levels and dynamic plantar pressures, respectively, for 73 overweight and obese prepubertal children. The results of this study revealed a significant and inverse correlation between the objectively measured physical activity levels and the dynamic plantar pressures generated by the children during walking, confirming the study hypothesis that children who generated higher plantar pressures would have lower levels of physical activity. Although it was acknowledged that the correlation values for this finding were low, it is recommended that the effects of long-term excessive body mass on participation in physical activity due to foot pain or discomfort be further investigated. Furthermore, as overweight and obese children need to be more physically active in order to enjoy the health benefits associated with an active lifestyle, the effects of increased physical activity, particularly increased weight-bearing physical activity, on the feet of overweight and obese children should also be researched. Therefore, in

Chapter 6, the foot structure and function of overweight and obese children recruited to a physical activity intervention program were investigated.

Baseline measurements of foot structure, dynamic plantar pressures and objectively-measured physical activity were collected for 24 overweight and obese children (8.5 ± 1.1 y) prior to them participating in a 10-week face-to-face weight-bearing physical activity program, which was followed by a maintenance period and a follow-up testing at 6 months. The results of these children were then compared to baseline and 6-month measurements for the same variables for a group of overweight and obese children who were not randomly assigned to the physical activity program. Although participation in this physical activity program did not result in the overweight and obese children spending more time being physically active after 6 months, it did result in stabilisation of body mass. Furthermore, the plantar pressures generated beneath the feet of these overweight and obese children during walking also remained stable after the 6-month period, although the time over which the pressures were generated significantly increased. Although participation in a weight-bearing physical activity program did not appear to alter foot structure and function in overweight and obese children, their developing feet may still be at risk of pain and discomfort during weight-bearing physical activity due to the high plantar pressures that they experience in everyday activities such as walking.

Conclusion

Higher plantar pressures generated during gait by overweight and obese school-aged children were not compensated for by the increased medial midfoot fat pad thickness characteristic of their feet. However, these higher dynamic plantar pressures were associated with a reduced level of participation in physical activity. Encouraging

overweight and obese school-aged children to participate in a weight-bearing physical activity intervention stabilised their body mass and, in turn, stabilised the dynamic plantar pressure distributions they generated during walking. However, overweight and obese children's feet may still be at risk of foot pain and discomfort during weight-bearing physical activity, even after stabilising their body mass, because the dynamic plantar pressure values in this sample of children remained high, and the pressure-time integral values generated by these children increased, after a 6 month period. As the feet must support an individual's body mass during weight-bearing physical activity and recommendations state that children need to increase active behaviour, continual excessive loading of the feet of overweight and obese school-aged children may result in structural and functional compromise during the developmental years. Therefore, interventions designed to reduce pressures generated beneath the feet of overweight and obese young children, while maintaining the necessary levels of fitness required for well-being, need to be developed.

Recommendations for Further Research

The following recommendations for further research are based on the findings of this thesis:

- 1) Further research should investigate the histology and function of fatty deposits within children's feet to determine developmental changes through infancy into childhood and how these might impact on foot mechanics. As the clinical relevance of significant differences between the medial midfoot fat pad thickness values and internal arch height measures for overweight and obese children compared to normal-weight children have not been determined it is recommended that studies be conducted to examine these foot characteristics.

- 2) Due to the nature of overweight and obesity, such that increases in body mass are gradual, tracking of a large cohort of children needs to be conducted to determine the long-term effects of continually carrying excess adiposity on foot development from childhood, to adolescence and into adulthood.
- 3) With the knowledge that higher pressures generated beneath the feet contribute to foot pain and discomfort, the feet of overweight and obese children need to be monitored during physical activity and physical activity intervention programs to avoid the development of foot problems as these children age, which might contribute to their reluctance to participate in physical activity.
- 4) Longitudinal research is also required to explore the possibility of reducing pressures generated beneath the feet of overweight and obese young children while maintaining the necessary levels of fitness required for well-being. Research could examine, for example, the effect of participating in non-weight-bearing physical activities, such as cycling and swimming compared to weight-bearing activity, on foot structure and function in overweight and obese children.