School of Physiotherapy

PLANTAR PRESSURE DISTRIBUTION BEFORE AND AFTER HALLUX VALGUS AND HALLUX LIMITUS SURGERY

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STATEMENT OF ORIGINALITY

This thesis is presented for the degree of Doctor of Philosophy at Curtin University of Technology, Western Australia. Studies were undertaken through the Department of Podiatry, School of Physiotherapy, between March 1997 and February 2001.

This research program was developed in association with my thesis supervisors who have been involved in editing both this thesis and the associated publications arising from this work. However, I have independently performed all of the experimental work and analysis of the results. All material presented in this thesis is original, apart from that acknowledged from other sources within the text.

Alan R. Bryant 15/8/01

ABSTRACT

Hallux valgus and hallux limitus are two common foot pathologies that may require surgical intervention. While the modified Austin bunionectomy and the Youngswick osteotomy/cheilectomy respectively, are often used to correct these conditions, insufficient research has been published regarding the effects of these procedures on plantar pressure distribution of the foot. This thesis involves a series of six studies investigating topics relating to radiographic measurements and plantar pressure distribution over a two-year period, in normal feet and in hallux valgus and hallux limitus feet before and after corrective surgery.

A review of the literature is presented relating to the development of plantar pressure measurement technology, the aetiology and surgical management of hallux valgus and hallux limitus, the reliability of the EMED system used in the studies, and the related clinical uses of plantar pressure measurement.

An initial study was designed to investigate the reliability of plantar pressure measurements using a simplified two-step method of data collection as compared to the traditional mid-gait technique of ten normal asymptomatic subjects. Intra-class correlation coefficients were calculated and compared for the pressure variables of contact area, contact time, maximum force and peak pressure of ten regions of the foot.

A study to determine normal reference range values for the EMED-SF system was then conducted using thirty healthy subjects and the two-step method of data collection. Descriptive statistical reporting of peak pressure, mean pressure and pressure-time-integrals were presented for ten regions of the foot.

Three related studies on radiographic and plantar pressure measurement differences, and their relationships were made using thirty normal, hallux valgus and hallux limitus feet. Various angular and linear radiographic measurements were tested for intra-rater reliability of measurement and pressure variables of peak pressure, mean pressure and

pressure-time-integral of 10 regions of the foot were recorded and one way analysis of variance employed to assess any significant differences.

Finally, two independent two-year prospective studies were designed to investigate the effects of the modified Austin bunionectomy for hallux valgus and the Youngswick osteotomy/cheilectomy for hallux limitus on plantar pressure distribution of the forefoot. In addition, fundamental radiographic measurement changes of the forefoot of hallux valgus subjects and range of motion changes of the first metatarsophalangeal joint of hallux limitus subjects were conducted. Thirty-six healthy volunteers acted as control subjects, 31 subjects (44 feet) with hallux valgus and 17 subjects (23 feet) with hallux limitus were included in the study. Using an EMED-SF system, plantar pressure variables of peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral were recorded at six regions of the forefoot, pre-operation and repeated at three, six, 12, 18 and 24-months post-operation for surgical subjects. Control subjects were tested at zero and 24-months. Descriptive statistics, multivariate and univariate analysis of variance with contrasts, t-tests of significance and correlations between certain measurement parameters were used in the analysis of the results.

The findings of these studies suggest that the two-step method of data collection of plantar pressure measurements is more reliable that the traditional mid-gait technique for most pressure variables. Consequently, the two-step method was employed as the preferred method of data collection in this series of studies.

With respect to radiographic differences between normal, hallux valgus and hallux limitus, it appears that hallux valgus feet have significant increases in metatarsus primus varus and first metatarsal protrusion distance, while hallux limitus feet have increased hallux abductus interphalangeal angles. Comparison of pressure variables between each group demonstrate hallux valgus feet have a medial localisation of peak pressure beneath the first, second and third metatarsal heads, suggesting that hyperpronation of the foot is associated with the development of hallux valgus. Hallux limitus feet on the other hand, show increased pressure beneath the hallux, third and fourth metatarsals and lesser toes, indicating a more lateral locus of pressure loading, suggestive of the foot functioning in a more supinated position. No significant relationship was found between any radiographic parameter and pressure variable tested in either group of subjects.

Plantar pressure measurement changes show the greatest variation during the initial three to six months following surgical treatment of hallux valgus and hallux limitus. The Youngswick osteotomy/cheilectomy for the treatment of hallux limitus produces near-normal range of motion of the first metatarsophalangeal joint. Pressures of the first metatarsal head remain relatively constant over the period of measurement, while a significant reduction of the hallux and lateral metatarsals were noted, related to increased dorsiflexion of the hallux. Pressures of the second metatarsal head remained significantly above pre-operation levels. The modified Austin bunionectomy for the treatment of hallux valgus produced 24-month radiographic changes consistent with accepted values. Pressure variables of the hallux reduced to normal values, with the first metatarsal head demonstrating an initial significant decrease and subsequent increase by twelve months post-operation to remain with the second metatarsal head at relatively similar values to pre-operation measurements.

The research demonstrates the two-step method of data collection is a viable means of obtaining reliable plantar pressure measurement data in the clinical situation. The investigations into radiographic and plantar pressure distribution indicate that structural radiographic and functional differences exist between normal, hallux valgus and hallux limitus feet. However, no relationship could be found between any of the radiographic parameters and pressure variables tested.

The modified Austin bunionectomy for hallux valgus significantly reduced fundamental radiographic measurements to accepted post-operative values, while the Youngswick procedure for hallux limitus significantly increased the amount of post-operative dorsiflexion of the hallux to normal values. The research demonstrates that immediate and longer-term functional changes to the forefoot occur following the surgical treatment of hallux valgus and hallux limitus, however plantar pressure measurements do not return

to normal values. No correlation was found between plantar pressure measurements and post-operative radiographic measurements in the hallux valgus group. However, the increased amount of dorsiflexion of the hallux post-operatively in the hallux limitus group was correlated with reduced lateral loading of the forefoot. Post-operation changes of plantar pressure distribution indicate that the rehabilitative period required to achieve stable foot function is between twelve to eighteen months. Furthermore, plantar pressure measurement technology offers the clinician a useful tool to monitor foot function prior to and following therapeutic intervention.

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CHAPTER ONE

DEVELOPMENT OF THE PROBLEM

1.0 INTRODUCTION

Hallux valgus and hallux limitus are two of the most common painful, related foot conditions that effect the lower extremity (Landers, 1992). Podiatric and orthopaedic surgeons employ a range of operative procedures that attempt to correct these deformities, however little research has been conducted to quantify changes to foot function following surgical intervention of this type. Most research into the effects of foot surgery focuses on radiographic changes and/or patient satisfaction surveys, with scant emphasis being placed on measuring pre- and post-operation foot function.

Computerised plantar pressure measurement systems that have become smaller, transportable, less expensive and more accurate and reliable in recent years, offer the researcher useful objective measurements of pressure, force and time parameters that may be applied to further understandings of foot function. Equally, the use of such force platform systems offers the practicing clinician a potentially valuable tool to help evaluate physical characteristics of a patient's foot before and after interventative treatment. The foot is essentially a complex weight-bearing structure that lends itself well to plantar pressure studies.

This doctoral thesis commences with an overall review of the relevant literature pertaining to hallux valgus and hallux limitus, and of the evolution and use of plantar pressure measurement systems and their clinical applications. Chapters Three to Nine are discrete studies where the methodology, results and discussion are confined to each of these sections. Each of these chapters are inter-related and commence with a 'rationale of the study' which briefly describes the deficiencies in the literature and the need for the particular study. Chapter Ten summarises the pertinent findings of each preceding chapter, presenting conclusions that link the separate studies, followed with recommendations for future research.

1.1 STATEMENT OF THE PROBLEM AND PURPOSES OF THE STUDIES

1.1.1 A comparison of the reliability of plantar pressure measurements using the two-step and mid-gait methods of data collection (Chapter Three)

Problem

The traditional and accepted protocol for collecting force platform data is the mid-gait technique. However, this method demands considerable floor space, is time-consuming for the researcher and patient to perform necessary repeated trials, and is unsuitable for many patients, for example those with insensate feet, cardiac or certain neuromuscular conditions, or vision impairment. By comparison, the two-step technique places less demand on the physical setting and on the patient undergoing testing. The reliability of results obtained from the two-step method compared with the mid-gait technique has not been adequately described in the literature.

Purpose

The purpose of this study was to compare and contrast the reliability of various base-line plantar pressure variables, such as contact area, contact time, maximum force and peak pressure, recorded via the mid-gait and two-step data collection techniques, using the EMED-SF system.

1.1.2 Normal values of plantar pressure measurements using the EMED-SF system (Chapter Four)

Problem

Previous research to establish normal values of common pressure parameters have been conducted using the traditional mid-gait data collection method and force platform systems other than the EMED-SF system used in this series of studies and by an increasing number of researchers. However, normative data for the EMED-SF system using the two-step method of data collection has not been described in the literature.

Purpose

The purpose of this study was to establish normal reference range values of selected plantar pressure measurements of ten regions of the foot using the EMED-SF system and the two-step method of data collection.

1.1.3 A comparison of radiographic measurements in normal, hallux valgus and hallux limitus feet (Chapter Five)

Problem

Weight-bearing radiographic measurements are frequently used by podiatrists to evaluate the foot prior to surgical or orthotic intervention and to monitor the progress and results of such treatment. While numerous studies have investigated the differences between normal and hallux valgus feet, there have been no studies identified that compare radiographic findings of normal, hallux valgus and hallux limitus feet.

Purposes

The purposes of this study were to:

(i) Review the intra-rater reliability of measurement of various radiographic parameters;

(ii) Investigate the differences of dorso-plantar and lateral radiographic measurements between normal, hallux valgus and hallux limitus feet.

1.1.4 Plantar pressure distribution in normal, hallux valgus and hallux limitus feet (Chapter Six)

Problem

The relationship between plantar pressure distribution and hallux valgus/hallux limitus has not been adequately researched. Reports in the literature that do exist for both hallux valgus and hallux limitus, demonstrate considerable variation in methodology, data collection techniques and pressure recording equipment. No study has been published comparing pressure distribution differences between hallux valgus and hallux limitus feet.

Purposes

The purposes of this study was to compare plantar distribution of pressure variables in normal, hallux valgus and hallux limitus feet using the EMED-SF system and the two-step method of data collection.

1.1.5 Radiographic measurements and plantar pressure distribution in normal, hallux valgus and hallux limitus feet (Chapter Seven)

Problem

Only two reports exist in the literature concerning the relationship between foot structure, as determined by weight-bearing radiographs, and foot function, as determined by plantar pressure distribution. Both reports investigated the relationship between weight-bearing x-rays and static peak pressure measurements, testing only three regions of the foot.

Purposes

The purposes of this study was to investigate the relationship between various static osseous radiographic and dynamic peak pressure measurements of ten regions of the foot using the EMED-SF system and the two-step method of data collection.

1.1.6 Plantar pressure measurement changes of the forefoot and range of motion of the first metatarsophalangeal joint following hallux limitus surgery (Chapter Eight)

Problem

The Youngswick osteotomy for the correction of hallux limitus is often used by podiatric and orthopaedic surgeons for appropriately selected patients. The few studies that have been published concerning pressure distribution after 1st metatarsophalangeal joint surgery have often been conducted with less than optimal adherence to methodology, and have investigated a variety of operations, using different platform systems and data collection techniques. Reports pertaining specifically to plantar pressure distribution following the Youngswick osteotomy have not been published. Similarly, changes to the available range of motion of the first metatarsophalangeal joint after this operation for hallux limitus have not been published.

Purposes

The purposes of this study were to:

(i) Investigate changes to various plantar pressure, force and time parameters of the forefoot over a twenty-four month period of patients with grade I or II hallux limitus undergoing a Youngswick osteotomy procedure.

(ii) To assess the range of motion of the hallux at the first metatarsophalangeal joint in hallux limitus feet following corrective surgery.

(iii) To evaluate the relationship between range of motion of the hallux and plantar pressure distribution in hallux limitus feet following corrective surgery.

1.1.7 Plantar pressure measurement changes of the forefoot and radiographic changes of the first metatarsophalangeal joint following hallux valgus surgery (Chapter Nine)

Problem

The modified Austin bunionectomy for the correction of hallux is widely used by podiatric and orthopaedic surgeons in the treatment of mild to moderate hallux valgus deformity. As with hallux limitus, only a few studies have been published concerning plantar pressure distribution after bunion surgery, often with less than optimal adherence to methodology, examining various operations, using different platform systems and data collection techniques. Reports of research examining a range of pressure/force variables of the forefoot over time following the modified Austin bunionectomy have not been published.

Purposes

The purposes of this study were to:

(i) Investigate changes to various plantar pressure, force and time parameters of the forefoot over a twenty-four month period in patients with hallux valgus undergoing a modified Austin bunionectomy procedure.

(ii) To evaluate essential radiographic changes to weight-bearing dorso-plantar radiographs of hallux valgus subjects following corrective surgery.

1.2 SIGNIFICANCE OF THE STUDY

Podiatrists have been performing elective foot surgery in Australia since the mid-1970's, corresponding with evolving post-graduate education and the introduction of local anaesthetic agents into the practice of podiatry. For many years now, the practical training of podiatric surgeons in Australia has included the surgical management of hallux valgus and hallux limitus. While there are relatively few podiatric surgeons in Australia, they account for approximately 10-15% of all elective foot surgery performed (Bennett & Patterson, 1997). Given that hallux valgus and hallux limitus are common symptomatic foot conditions, particularly in the over sixty-five age group (Weiner & Steinwachs, 1984; Levy, 1992; and Bennett, 1994), and that the population is aging, the need to provide safe and effective evidence-based podiatric surgical services is of paramount importance.

Plantar pressure distribution studies offer the researcher and clinician a potentially reliable and objective means of quantifying a measure of foot function, pre-and post-therapeutic intervention. This study examines for the first time, changes to plantar pressure distribution following two commonly performed podiatric surgical procedures to correct hallux valgus and hallux limitus.

1.3 DEFINITION OF TERMS

'Hallux valgus' is the deformity of the first metatarsophalangeal joint of the foot where the head of the first metatarsal is prominent, the hallux is abducted towards the second toe and everted or rotated inwardly about its longitudinal axis. Often referred to as 'hallux-abducto-valgus' in the podiatric literature.

'Hallux limitus' is the deformity of the first metatarsophalangeal joint of the foot where there is significant degenerative arthrosis of the joint so as to markedly limit the passive and active range of motion of the hallux on the first metatarsal head. Often referred to as 'hallux rigidus' in the orthopaedic literature.

'Mask' is a defined topographical region of interest of the foot, such as the area beneath the first metatarsal head.

'Sensor' is the smallest area of the force platform capable of producing a separate pressure measurement.

'Frame' contains the values of pressure for each sensor of the measuring system at a discrete moment in time. The length of the data file (number of frames) is determined by the frequency of the recording system.

'Peak pressure' (N/cm2) is the maximum pressure measured of a single sensor within the mask being examined.

'Average pressure' (N/cm2) is calculated by dividing the total force in the mask (i.e. the summation of all of the forces acting on each individual sensor) by the contact area of that mask being examined.

'Pressure-time-integral' (N/cm2)s is the pressure 'impulse' and is the summation of the peak pressure values that occurred in each frame, multiplied by the frame interval or time for the frame, and represents the area under the peak pressure-time. It is the area under the peak pressure time curve.

'Roll-over-process' is the phase of gait from the beginning of heel contact to the end of toe-off.

'Contact time' (% ROP) is the average contact time of each sensor in a mask as a percentage of the total roll-over-process.
'Maximum force' (% body wt) is the maximum force that occurred in each mask at some instant in time, i.e. the peak value for the force-time-curve.

'Force-time-integral' (% body wt)s is the force 'impulse' and is the summation of the maximum force values that occurred in each frame, multiplied by the frame interval or time for the frame, and represents the area under the mean maximum force-time curve for each mask being examined.

1.4 RESEARCH HYPOTHESES

(i) Plantar pressure data collected using the two-step method of data collection are as reliable as that collected using the midgait method of data collection.

(ii) Radiographic measurements of normal feet are different from radiographic measurements of hallux valgus or hallux valgus feet.

(iii) Plantar pressure measurements of normal feet are different from plantar pressure measurements of hallux valgus or hallux limitus feet.

(iv) Dynamic plantar pressure distribution in normal, hallux valgus and hallux limitus feet is related to static weight-bearing radiographic measurements of the foot.

(v) Plantar pressure measurements of the forefoot of feet with hallux limitus change to approximate normal values following the Youngswick cheilectomy/osteotomy.

(vi) The Youngswick cheilectomy/osteotomy improves passive range of motion of the first metatarsophalangeal joint to normal values in hallux limitus feet.

(vii) The modified Austin bunionectomy procedure improves radiographic parameters to normal values.

(viii) Plantar pressure measurements of the forefoot of feet with hallux valgus change to approximate normal values following the modified Austin bunionectomy.

1.5 SUMMARY

The purpose of this thesis therefore, is two-fold. Firstly, to further advance the clinical application of plantar pressure measurement and secondly, to investigate the functional and structural effects of surgery on hallux valgus and hallux limitus.

As a weight-bearing structure, designed to support and transport the body, the foot is uniquely amenable to plantar pressure distribution studies. Computerised force platforms, once large, expensive, and often unreliable pieces of equipment, found only in university or hospital gait laboratories, are now commercially available with the attributes of being small, transportable and increasingly accurate. The transition of the use of modern force platforms from the research laboratory into clinical practice depends, to a large degree, upon the outcomes of investigations into the clinical use and relevance of plantar pressure distribution as a diagnostic and clinical monitoring tool.

The desire to add to the body of knowledge relating to the potential clinical use of plantar pressure distribution prompted the development of this project. This thesis is composed of a series of related studies investigating aspects of hallux valgus and hallux limitus using a combination of radiographic and plantar pressure measurements.

CHAPTER TWO
REVIEW OF LITERATURE

2.0 INTRODUCTION

Various technologies, including force platforms and in-shoe devices, have been developed in an attempt to provide reliable and reproducible methods of recording plantar pressure distribution to improve the understanding of foot function in both normal and pathological subjects (Alexander et al., 1990; Morlock, 1991; Cavanagh, et al., 1992). From a clinical perspective, objective documentation of foot structure and function before and after therapeutic intervention is essential to assess critically the results of such treatment (Jahss, 1984). The successful application of this technology is dependent upon an understanding of its research and clinical applications and the limitations inherent in the equipment and methodologies employed. This chapter examines the effects on foot function of two common forefoot deformities, hallux valgus and hallux limitus and compares these with normal feet, as assessed by radiographic measurements and plantar pressure distribution.

The review of the literature has been divided into the following sections:

a. Anatomy of the first metatarsophalangeal joint.
b. Incidence and aetiology of hallux valgus and hallux limitus.
c. Radiographic assessment of hallux valgus and hallux limitus.
d. Surgical management of hallux valgus and hallux limitus.
e. A summary of the development of plantar pressure measurement systems.
f. Reliability of plantar pressure measurements using the EMED® system.
g. Factors influencing plantar pressure measurements.
h. Clinical application of plantar pressure measurements

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2.1 ANATOMY OF THE FIRST METATARSOPHALANGEAL JOINT

The first metatarsophalangeal joint is a synovial joint consisting of the articular surfaces of the first metatarsal head and the base of the proximal phalanx of the hallux. Two sesamoid bones articulate in grooves beneath the plantar aspect of the first metatarsal head and are an integral part of the joint apparatus. Being a modified hinge joint, the primary direction of motion is in the sagittal plane (dorsiflexion and plantarflexion), with a small amount available in the transverse plane (abduction and adduction), and no motion normally available in the frontal plane (inversion and eversion) Root et al. (1977).

The ligamentous attachments of the first metatarsophalangeal joint are complex. On the medial aspect of the joint, the tibial collateral, tibial sesamoidal and plantar tibial sesamoidal ligaments are found. While on the lateral aspect of the joint a similar arrangement of intra-articular ligaments are present, namely, the fibular collateral, fibular sesamoid and plantar fibular sesamoidal ligaments (McCarthy, 1987). In addition, an intersesamoidal ligament, the joint capsule proper and the deep plantar transverse ligaments complete the strong capsular and ligamentous structures. Refer to Figure 2.1.

The tendons of muscles associated with the joint comprise the extensor hallucis longus (EHL) found dorsally and slightly lateral to the midline of the joint, with extensor hallucis brevis lateral to this tendon and a small tendon slip from EHL medially, sometimes referred to as extensor hallucis capsularis (McCarthy, 1987). Plantarly, the tendon of flexor hallucis longus courses between the sesamoids to insert into the plantar aspect of the distal phalanx. The flexor hallucis brevis muscle, whose short tendon connects plantarly into the sesamoid bones, becomes continuous with the plantar sesamoidal ligaments to insert into the plantar aspect of the proximal phalanx of the hallux. The intrinsic muscles of abductor hallucis and adductor hallucis approach the joint from the medial and lateral aspects to attach into the medial and lateral sesamoids respectively, to complete the soft tissue structures of the joint (McCarthy, 1987). Refer to Figure 2.2.

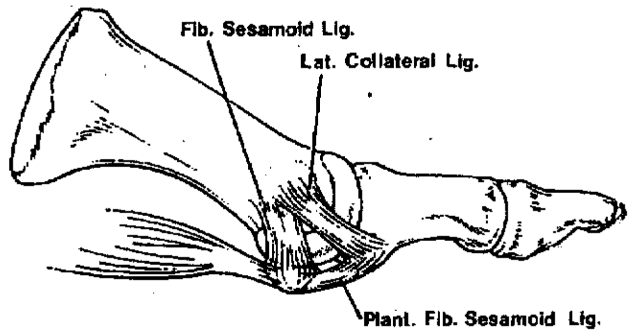

Figure 2.1 Lateral view of ligamentous structures of the first metatarsophalangeal joint (Adapted from Laden & Marcus, 1993)

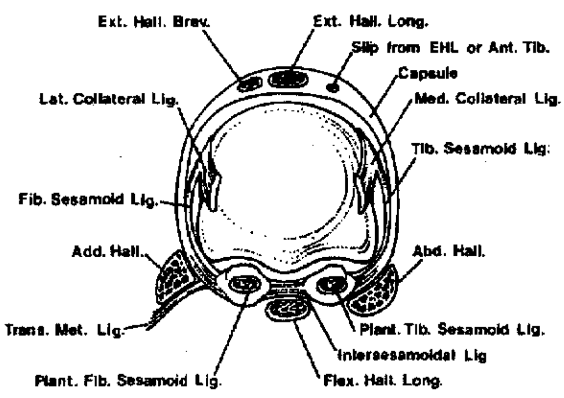

Figure 2.2 Cross-sectional view of musculo-tendinous structures of first metatarso-phalangeal joint (Adapted from Laden & Marcus, 1993)

2.2 Incidence And Aetiology Of Hallux Valgus And Hallux Limitus

2.2.1 Incidence of hallux valgus

Hallux valgus (bunion deformity) has been described as "one of the most common structural deformities found in the lower extremity" (Landers, 1992, p. 459). The incidence of hallux valgus in the general population has been variously reported in the literature, ranging from almost non-existent (McLennan, 1966), to approximately 50% in a study of South Africans (Gottschalk et al., 1981).

Hallux valgus would appear to be present in many patients as children or young adults, with the symptoms tending to increase with age. Cole (1959), reported an incidence of hallux valgus of 36% in schoolchildren between 8-18 years. Piggott (1960), reported 57% of adults patients with hallux valgus recalled having the deformity in their teens or earlier. While the classic article by Hardy and Clapham (1951), stated that 46% of their adult patients with hallux valgus had the deformity by the age of 20.

An epidemiological survey in the USA found the incidence of symptomatic hallux valgus to be 1:33 among Caucasians and 1:8 among African Americans in the 15-30 year age group with a male:female ratio of 1:2. For the 31-60 year age group the ratio was 1:11 Caucasians and 1: 5.5 African Americans, and is as high as 1:6 Caucasians and 1:3 African Americans in people over 60 years of age. The male:female ratio for all people in the 31-60 and 31-60 year age groups is approximately the same at 1:4 (Gould et al., 1980). A similar survey in rural Queensland demonstrated an overall incidence of symptomatic bunion deformity of 9.0% with a male:female ratio of approximately 1:2, with the condition being more prevalent in people over 45 years of age (Nancarrow, 1999).

Research conducted in Australia by the NSW Health Department demonstrated an incidence of symptomatic hallux valgus deformities in 7.4% of the population surveyed. The condition was found to be more prevalent with advancing age (NSW Health Department, 1991). In a survey of adult diabetic patients and non-diabetic controls, Foley (1991) found bunion deformities to be present in 5% of male and 21% of female subjects studied, a finding supported by other researchers (Black & Hale, 1987; Cartwright & Henderson, 1986; Merrill et al., 1967).

From the reports cited it is apparent that while the incidence of hallux valgus varies considerably without any firm consensus of opinion, hallux valgus may be regarded as a common foot deformity, more prevalent in women, with an increasing incidence of symptomatology directly associated with age.

2.2.2 Incidence of hallux limitus

Hallux limitus, or painful restriction of first metatarsophalangeal joint motion, is said to be the second most common structural foot deformity to hallux valgus (Dananberg et al., 1996). In the United States, the incidence of hallux limitus has been reported as 1:300 Caucasians and 1:50 African Americans in the 15-30 year age group with an equal male:female ratio. In the 31-60 year age group the incidence is reported to be 1:60 Caucasians and 1:100 African Americans with a male:female ratio of 8:1, and over the age of 60 years it increases to 1:45 Caucasian and 1:35 African Americans with a male:female ratio of 2:1 (Gould et al., 1980). The incidence of hallux limitus in Australia has not been reported.

2.2.3 Aetiology of hallux valgus

The influence of footwear has long been cited as a major factor in the development of hallux valgus (Sim-Fook & Hogdson, 1958; Charlesworth, 1961; Shine, 1965; Clough & Marshall, 1985; Kusumoto et al., 1996), although Root et al. (1977) maintain there is no evidence that shoes cause bunion deformities in feet that function normally.

A positive family history of hallux valgus is thought to be strongly associated with the deformity (Hardy & Clapham, 1951; Glynn et al., 1980), as is systemic arthritides (e.g. rheumatoid and psoriatic arthritis), neuromuscular disorders (e.g. cerebal palsy) and traumatic causes (Root et al., 1977). Less commonly, other factors including genetic disorders or syndromes, such as Ehler-Danlos syndrome, Marfan's syndrome or generalised ligamentous laxity may be associated with the deformity (McNerney & Johnston, 1979; Caputo & Walter, 1983).

Biomechanical and structural influences are often considered the most important aetiological factors contributing to the development of hallux valgus, and are often associated with a genetic predisposition to the deformity (Landers, 1992; Hardy & Clapham, 1951; Glynn et al., 1980). Excessive pronation of the foot during the stance phase of gait leads to acquired hypermobility of the first ray of the foot, producing abnormal stresses and deforming forces at the first metatarsophalangeal joint level (Inman, 1974; Root et al., 1977; Mann & Coughlin, 1981; Mann, 1982; Roukis et al., 1996).

The importance of flexor hallucis longus in the pathomechanics of hallux valgus has been investigated by Snijders et al.(1986). Using a Kistler force plate and electromyography, these authors suggested that the deformity is associated with increased strength of this muscle. Shimazaki and Takebe (1981), demonstrated that dynamic imbalance of the intrinsic muscles around the first metatarsophalangeal joint was associated with the deformity, secondary to structural changes related to excessive rearfoot pronation. This view is in keeping with that of Stephenson (1990), who compared the biomechanical findings of 62 subjects with symptomatic hallux valgus and 62 normal subjects. Using linear logistic regression, he found the best predictor for the development of hallux valgus was the degree of pronation of the foot measured in static stance as the posterior bisection of the heel. He also found a significant positive correlation between the time at which subjects developed hallux valgus and the severity of the deformity, concluding that excessive pronation is a significant aetiological factor in hallux valgus and precedes the development of the deformity.

Metatarsus primus adductus is an almost universal feature of hallux valgus and has been described as one of the most significant radiographic findings related to the deformity, particularly when found in combination with generalised metatarsus adductus (Landers, 1992). Metatarsus primus adductus is more frequently seen in females than males (Hardy

& Clapham, 1952; Gottschalk et al., 1981), and, as women seem to develop the deformity more frequently than men, this suggests an association between metatarsus primus adductus and hallux valgus. In addition, a study comparing the radiographic differences between 52 feet with hallux valgus and 66 normal feet, the obliquity of the medial cuneiform, a cause of metatarsus primus adductus, was reported as the most significant feature of feet with hallux valgus (Saragas & Becker, 1995). Similarly, a direct relationship between first metatarsal eversion and the size of the first intermetatarsal angle has been demonstrated radiographically (Eustace et al., 1993). The importance of metatarsus primus adductus as an aetiological factor in hallux valgus has been reafirmed in a recent radiographic study (Tanaka et al., 2000). These authors reviewed measurements of weight-bearing dorso-plantar x-rays from 229 feet of 144 patients with symptomatic hallux valgus and compared them with 94 normal feet. They found that hallux adductus, metatarsus primus adductus and proximal articular set angles were significantly higher in hallux valgus feet.

The relationship between metatarsus adductus and hallux valgus has often been reported in the literature without consensus of opinion. While most authors believe a causal relationship exists (Root et al., 1977; La Reaux & Lee, 1987; Griffiths & Palladino, 1992), this proposition is disputed by Kilmartin et al. (1991), who found no association between metatarsus adductus and hallux valgus in juvenile subjects.

The relative position of the sesamoids beneath the first metatarsal head is another radiographic variable thought to contribute to the development of the condition. The lateral displacement of the sesamoids upon the first metatarsal head is thought to be due to the lateral displacement of the hallux and subsequent erosion of the central plantar cristae under the first metatarsal head (Alvarez et al., 1984; Pressman et al., 1986). The relative position of the medial sesamoid beneath the first metatarsal head may be recorded as a categorical measurement on a scale of one to seven, and has been reported in the literature as being three or less in normal feet and four or more in hallux valgus feet (LaPorta et al., 1974; Hass, 1981; Steinbock & Hetherington, 1988; Landers, 1992; Laden & Marcus, 1993; Bryant & Singer, 1998).

The significance of the relative length of the first metatarsal compared with the second metatarsal in the development of hallux valgus has been variously reported. Villadot (1973), claimed that hallux valgus was associated with short first metatarsals while Saragas and Becker (1995), showed no significant association between first metatarsal length and hallux valgus in their radiographic study. This view contrasts with that of Heden and Sorto (1981), who compared weight-bearing radiographs of 100 normal with 200 symptomatic hallux valgus feet. Heden and Sorto (1981) found a significant relationship between the first metatarsal length and the presence of hallux valgus, with the first metatarsal being on average of 2.8mm longer than in normal feet. Similarly, Duke et al. (1982), also found a direct relationship between the relative length of the first metatarsal and the hallux abductus angle in hallux valgus feet.

From the literature, it is obvious that structural factors are considered by a majority of researchers to play an important role in the aetiology of hallux valgus. However, it is also clear that a consensus of opinion does not exist, supporting the need for further investigation in this area.

2.2.4 Aetiology of hallux limitus

Cotterill (1888), cited in Banks and McGlamry (1992), first coined the term hallux rigidus to describe a reduced or absent range of motion of the first metatarsophalangeal joint. Numerous aetiologies have been proposed, including major or micro-trauma (Giannestras, 1973; Root et al., 1977; Mann et al., 1979), degenerative joint disease secondary to systemic arthridites such as rheumatoid, gouty and psoriatic arthritis or septic arthritis (Kashuk, 1975; Root et al., 1977; Camasta, 1996).

Immobility of the medial column of the foot secondary to degenerative joint disease with developmental ankylosis of the first metatarso-cuneiform joint has been described as a cause of hallux limitus (Root et al., 1977; Banks & McGlamry, 1992). Similarly, adhesions involving the sesamoid/first metatarsal head articulation may displace the instantaneous centre of rotation of the first metatarsophalangeal joint in a plantar direction, creating dorsal impingement of the joint and secondary arthritic changes

(Camasta, 1996; Light, 1996). Osteochondritis dissecans of the first metatarsal head has been proposed as a further intrinsic cause of hallux limitus (Vilaseca & Ribers, 1980; Banks & McGlamry, 1992; Camasta et al., 1994).

A relationship between the amount of dorsiflexion available at the first metatarso-phalangeal joint and soft tissue structures has been proposed. Tightness of the flexor hallucis brevis has been suggested as an intrinsic cause of hallux limitus (Durrant & Siepert, 1993). Similarly, the relationship between tension in the plantar fascia and first metatarsophalangeal motion has been described in the literature (Hicks, 1954; Kappel-Bargas et al., 1998). More specifically, tightness of the medial band of the plantar fascia has been suggested as a contributing factor in the development of the disorder (Banks & McGlamry, 1992; Durrant & Siepert, 1993; Camasta, 1996).

While structural factors which may lead to the development of hallux limitus have been outlined in the literature, only first metatarsal length and sagittal plane alignment have been discussed in any depth. An increased relative length of the first metatarsal has been implicated since it appears to increase the compressive forces of the first metatarsophalangeal joint during late mid-stance and into the propulsive phase of gait (Root et al., 1977; Villadot, 1973; Vilaseca & Ribers, 1980; Banks & McGlamry, 1992). However, since these authors did not utilise controlled studies, they failed to demonstrate a significant association between first metatarsal length and the development of hallux limitus.

Metatarsus primus elevatus or a relatively dorsiflexed position of the first metatarsal is often reported to be a primary cause of hallux limitus (Jack, 1940; Root et al., 1977; Drago et al., 1984; Meyer et al., 1987; Camasta, 1996; Banks & McGlamry, 1992; Roukis et al., 1996). However, while Camasta (1994) has proposed a radiographic measurement technique to quantify metatarsus primus elevatus, and Glasoe et al. (1998) have outlined a clinical laboratory method of measuring the amount of first metatarsal dorsiflexion, neither technique has been applied to clinical research.

Therefore, the evidence supporting structural factors such as first metatarsal length and metatarsus primus elevatus as a primary cause of hallux limitus, is largely based on anecdotal clinical and radiographic findings. As most contemporary surgical procedures to correct mild to moderate cases of hallux limitus involve shortening and/or plantar flexion of the first metatarsal (Youngswick, 1982; Banks & McGlamry, 1992; Chang, 1996), these purported causes of hallux limitus deserve scientific investigation to justify the use of such surgical techniques.

2.3 Radiographic Assessment Of Hallux Valgus And Hallux Limitus

The importance of utilising radiographic measurements as an aid in planning corrective surgical procedures of the forefoot has been emphasised (LaPorta et al., 1974; Hass, 1981; Ruch et al., 1987; Steinbock & Hetherington, 1988). Measurements commonly used include hallux abductus angle, metatarsus primus adductus angle, hallux interphalangeal angle, first metatarsal protrusion distance, metatarsus adductus angle and tibial sesamoid position (Osher, 1994; LaPorta et al., 1974; Gentili et al., 1996). See Figures 2.3 and 2.4.

The American Orthopaedic Foot and Ankle Society formed a committee to develop a set of guidelines for clinical and radiographic measures to promote in-depth studies of hallux valgus using standardized methods of data collection (Smith et al., 1984). The Committee reported that standardising radiographic technique (patient positioning, radiographic technique) is of critical importance and is in accordance with the views of others (Gamble and Yale, 1975; Weissman, 1983; Christman, 1988; Christman & Peter, 1990).

Positioning of each patient in their own specific 'angle and base of gait' was thought to be critical for accurate and reproducible weight-bearing foot radiographs (Hlavac, 1967; Gamble & Yale, 1975; Weissman, 1983). However, recent research disputes the need for angle and base of gait x-rays, demonstrating no significant differences in numerous

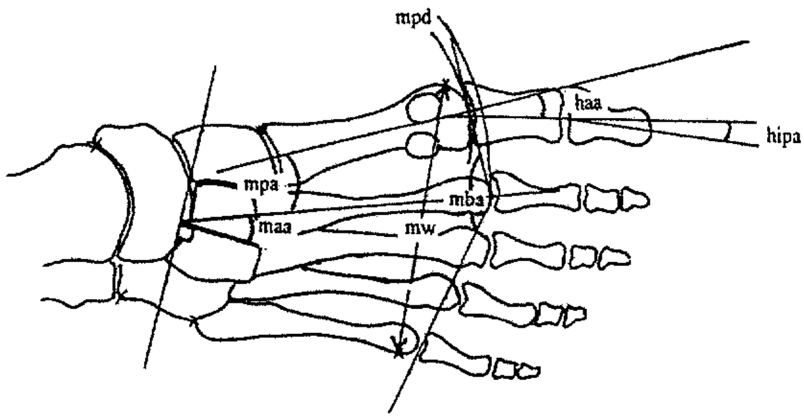

Figure 2.3 Standard dorso-plantar radiographic measurements for the evaluation of hallux valgus

haa = hallux abductus angle, mpa = metatarsus primus adductus,
hipa = hallux interphalangeal angle, mpd = 1st metatarsal protrusion distance, maa = metatarsus adductus angle, mba = metatarsal break angle, mw = metatarsal width

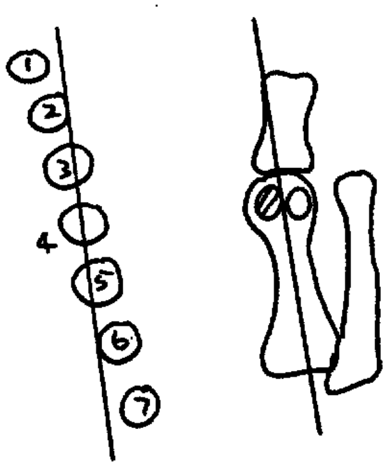

Figure 2.4 Assessment of tibial sesamoid position from dorso-plantar radiograph
Adapted from Gerbert (1991)

radiographic parameters between these and simple feet-together weight-bearing x-rays (Bryant, 1997).

With respect to the effect of radiographic technique on x-ray image, Camasta et al. (1991) demonstrated 10-20% magnification of metatarsals, dependent upon the subject to film distance. Their findings suggest that image magnification and distortion *between* subjects may be found due to variation in arch height and shape between individuals. The influence of positioning of the extremity to be radiographed was also investigated by Green and Green (1994), who found that actual deformities of long bone were usually underestimated on x-ray by approximately 10%, unless the part was positioned parallel to the x-ray film. However, provided radiographic technique is standardised, repeated intra-subject radiographic measurements should remain relatively constant. This view is supported by the findings of Bryant (1997).

2.3.1 Radiographic findings in hallux valgus

Radiographic assessment of the hallux valgus foot usually involves the measurement of certain parameters of weight-bearing dorso-plantar x-rays. These include the hallux abductus angle, the metatarsus primus adductus angle, the first metatarsal protrusion distance, and the tibial sesamoid position.

The normal hallux abductus angle is considered to be 5-15° (LaPorta et al., 1974; Hass, 1981; Smith et al., 1984; Steinbock & Hetherington, 1988; Laden & Marcus, 1993; Osher, 1994), while the normal metatarsus primus adductus angle is considered to be less than 12° (LaPorta, 1974; Hass, 1981; Smith, 1984; Steinbock, 1988; Laden, 1993; Gentilli, 1996). The first metatarsal protrusion distance, relative to the second metatarsal is considered to be +/- 2mm (LaPorta et al., 1974; Hass, 1981; Smith et al., 1984; Steinbock & Hetherington, 1988; Laden and Marcus, 1993). The normal tibial sesamoid position is reported to be 3 or less, measured on a scale of 1-7, relative to the longitudinal bisection of the first metatarsal (LaPorta et al., 1974; Hass, 1981; Steinbock & Hetherington, 1988; Laden & Marcus, 1993).

While normal reference range values of weight-bearing dorso-plantar radiographic parameters have been well documented, the list of possible measurements is not comprehensive, and there is a need to investigate the value of other dorso-plantar and lateral parameters and their relationship to hallux valgus.

2.3.2 Radiographic findings in hallux limitus

In contrast, radiographic assessment of hallux limitus is traditionally restricted to observing classic osteoarthritic changes, indicating the degree of osteoarthrosis present. Joint space narrowing, sclerosis (radiopacity, thickening) of the subchondral bone, osteophytic proliferation, flattening of the joint, sesamoid hypertrophy, and free bony fragments around the dorsal aspect of the joint are usually noted (Camasta, 1996).

While a complicated radiographic classification system has been proposed for hallux limitus (Hanft et al., 1993), a more succinct classification proposed by Regnauld (1986) would seem to be perfectly adequate. See Figure 2.5.

The two structural radiographic parameters of weight-bearing x-rays of hallux limitus considered in the literature include relative first metatarsal length (Villadot, 1973; Gerbert, 1991; Banks and McGlamry, 1992) and metatarsus primus elevatus (Camasta, 1994; Seiberg et al., 1994). Based upon a review of the literature, there seems to be an obvious deficiency of knowledge concerning the relationship between hallux limitus and other structural radiographic parameters.

2.4 Surgical Management Of Hallux Valgus And Hallux Limitus

2.4.1 Hallux valgus

Various surgical procedures to correct hallux valgus have been described since the late 1800's. The following is a summary of commonly employed surgical procedures for the treatment of hallux valgus, which may be grouped into five basic categories:

Grade I. Functional limitation of dorsiflexion, mild dorsal spurring, pain derived from dorsal hypertrophy, no structural sesamoid disease.

Grade II. Broadening and flattening of the metatarsal head and base of the proximal phalanx, joint space narrowing, structural first metatarsal elevation, osteochondral defect, sesamoid hypertrophy.

Grade III. Severe loss of joint space, extensive peripheral spurring, osteochondral defects of the metatarsal head +/- proximal phalanx, +/- joint mice, extensive sesamoid hypertrophy, loss of joint space, near ankylosis.

Figure 2.5 Radiographic grading system for hallux limitus (Regnauld, 1986).

2.4.1.1 Arthroplasty techniques of the first metatarsophalangeal joint.

Keller first described arthroplasty of the first metatarsophalangeal joint in 1904 (Keller, 1904). Others have advocated modifications of the Keller procedure in an attempt to produce more functional results by reducing some of the shortcomings inherent in this essentially, joint destructive procedure, (Swanson, 1972; McGlamry et al., 1973; Ganley et al., 1986). However, the Keller bunionectomy remains a procedure suitable for elderly patients with advanced deformity, where osteotomies of the hallux and/or first metatarsal are contraindicated.

2.4.1.2 Bunionectomy and soft tissue techniques

The simplest bunionectomy procedure is the removal of the medial eminence of the first metatarsal head and repair of medial soft tissue structures, as first described by Silver (1923). McBride (1928), suggested the inter-metatarsal angle could be reduced by excision of the lateral sesamoid and by transferring the adductor hallucis tendon from the lateral base of the proximal phalanx dorsally, to the medial aspect of the first metatarsal head. The McBride procedure is still used with good effect in selected patients in those with a mild-moderate deformity and with no significant arthritic changes of the first metatarsophalangeal joint, particularly in patients for whom first metatarsal osteotomies are contraindicated. The incidence of iatrogenic hallux varus (over-correction of the deformity), is however a significant risk, and therefore the technique must be performed with due care to avoid overzealous soft tissue correction (Ruch et al., 1987).

2.4.1.3 Distal first metatarsal osteotomies

Reverdin in 1881, was the first to describe a distal first metatarsal wedge osteotomy for the correction of hallux valgus, but because of the unstable nature of the osteotomy, it was rarely performed as described (Ruch et al., 1987). Modifications of the osteotomy to improve the stability, particularly the Green-Reverdin technique, to reduce the risk of aseptic necrosis of the distal fragment, and to afford protection to the plantar cristae of the first metatarsal head and sesamoids have been described (Ruch et al., 1987; Fenton & McGlamry, 1982; Laden & Marcus, 1993). While the modified Reverdin procedures potentially correct the intermetatarsal angle and proximal articular set angle, sagittal plane realignment of the metatarsal head is not possible.

A similar, but more aggressive bunionectomy proposed by Mitchell et al. (1958), has been described as the classic orthopaedic transpositional distal osteotomy of the first metatarsal head (Ruch et al., 1987). The main complication of the Mitchell osteotomy is a high incidence of first metatarsal shortening, leading to lesser metatarsalgia (Kinnard & Gordon, 1984).

The Austin bunionectomy (often termed 'Chevron' osteotomy in the orthopedic literature) is a horizontal transpositional 'V' osteotomy of the first metatarsal head, first reported by Dale Austin, an American podiatrist, in 1968 (Austin & Leventen, 1968). Austin later qualified as an osteopath and orthopaedic surgeon (Rutherford, 1998). The procedure however, was not described in detail in the literature until 1980 (Austin & Leventen, 1980).

The procedure has become an extremely popular one, with generally favourable results reported for correction of a moderate deformity (Ruch et al., 1987). The procedure is fundamentally designed to reduce a mild to moderately high intermetatarsal angle and to straighten the hallux by adductor hallucis tenectomy and tightening of the medial joint capsule. Figure 2.6 depicts the essential nature of the procedure, while a detailed description of the modified version of the Austin bunionectomy performed on hallux valgus subjects in this study is outlined in Appendix 1. The modifications employed include the use of a buried Kirschner wire fixation for improved stability (Knecht and VanPelt, 1981), angulation of the osteotomy to allow for slight plantar flexion and shortening of the first metatarsal head (Duke & Kaplan, 1984), and the use of an axis guide for accurate placement of the osteotomy (Boberg et al., 1987).

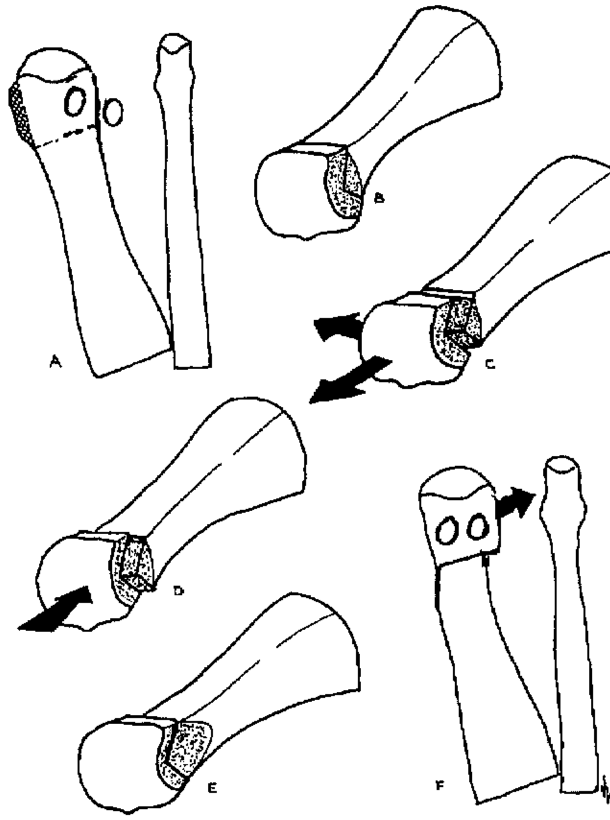

Figure 2.6 Diagrammatic representation of the Austin first metatarsal osteotomy

(A) ostectomy 1st metatarsal head; (B) transverse "V" osteotomy; (C, D) lateral repositioning of metatarsal head; (E) removal of resultant prominence of neck of 1st metatarsal; (F) final position of metatarsal head. Adapted from Gerbert (1991)

While substantial research including clinical, radiographic and subjective patient questionnaire studies have been published supporting the use of the modified Austin bunionectomy (Steinbock & Hetherington, 1988; Knecht & VanPelt, 1981; Bryant, 1996; Goforth et al., 1996; Petje et al., 1997; Trnka et al., 1997; Bryant & Singer, 1998), the effects of the procedure on plantar pressure distribution has not been adequately investigated.

2.4.1.4 Proximal first metatarsal osteotomies

Osteotomy of the base of the first metatarsal for the correction of hallux valgus was first described by Loison in 1901 and first performed by Balacescu in 1903 (Ruch et al., 1987). The technique was a closing transverse wedge osteotomy of the base of the metatarsal with no internal fixation.

The procedure has been modified and improved over the years. The use of an axis guide to improve the accuracy of the osteotomy cuts and the application of rigid internal fixation and a period of enforced non-weightbearing, has lead to more reliable postoperative results (Landers, 1992). More recently, a basal Austin type of osteotomy has been described with good effect (Borton & Stephens, 1994).

While this type of procedure is useful for severe hallux valgus with large intermetatarsal angles, it may only be performed as a unilateral procedure, and numerous complications such as metatarsus primus elevatus, first metatarsal shortening, hallux varus have been reported (Curda & Sorto, 1981; Haendel & Lindholm, 1982; Jeremin et al., 1982; Schuberth et al., 1984; Yu et al., 1996).

2.4.1.5 Miscellaneous procedures

A closing transverse wedge osteotomy of the proximal phalanx of the hallux was introduced in 1925, often referred to as the Akin osteotomy (Ruch et al., 1987). The procedure is useful to correct a hallux abductus interphalangeus deformity, or as an adjunctive procedure in the surgical treatment of hallux valgus. This procedure should not however, be used in isolation in the presence of a high intermetatarsal angle or marked lateral adaptation of the head of the first metatarsal (Gerbert & Sokoloff, 1981; Landers, 1992). As such, the Akin osteotomy will sometimes be performed in concert with an Austin osteotomy for the correction of hallux valgus with good results (Tollison and Baxter, 1997).

Arthrodesis or fusion of the first metatarso-cuneiform joint was first described by Lapidus (1960), and improved with the introduction of internal screw fixation

(Rutherford, 1974). The procedure has been described as producing excellent results, being designed to stabilise the first metatarsal and medial column of the foot while reducing a high inter-metatarsal angle (Hofbauer and Grossman, 1996). The procedure may only be performed unilaterally and requires internal fixation with an extended period of non-weight bearing. The technique has been associated with complications such as delayed or non-union, first metatarsal shortening, metatarsus primus elevatus and resultant metatarsalgia (Landers, 1992).

2.4.2 Hallux limitus

The mainstay of hallux limitus surgery for many years, in various modified forms, has been the Keller arthroplasty, first described in the early 1900's (Keller, 1904). As limitations and complications of the procedure render it undesirable for use in active younger patients with mild-moderate deformity, the search for effective alternative procedures has continued (Smith et al., 1987). The following is a summary of commonly employed surgical procedures for the repair of hallux limitus, which may be grouped into four basic categories:

2.4.2.1 Cheilectomy

Cheilectomy or chelotomy is the removal of the osteophytic proliferation around the first metatarsal head and base of the proximal phalanx of the hallux in an attempt to improve or restore the range of motion of the joint. It is universally regarded as the important "first step" in the surgical treatment of the condition and as a fairly innocuous procedure in its own right (Chang, 1996).

The success of cheilectomy as a single procedure in mild cases of hallux limitus has been reported with generally favourable results (Gould, 1981; Feldman et al., 1983; Mann & Clanton, 1988). Most often however, cheilectomy is performed in conjunction with additional soft tissue or osseous procedures designed to correct the existing underlying structural abnormalities (Chang, 1996).

2.4.2.2 Arthroplasty

The Keller arthroplasty is essentially a cheilectomy of the first metatarsal head with removal of the base of the proximal phalanx of the hallux to create a gap arthroplasty of the first metatarsophalangeal joint. Modifications of the Keller procedure (McGlamry et al., 1973; Ganley et al., 1986; Lombardo, 1989; Harper, 1995) have been developed to improve the stability and purchasing capacity of the hallux, and the use of joint implants (Swanson, 1972; Pontell & Gudas, 1988).

The reported complications of the Keller procedure include decreased forefoot stability and great toe purchase, resulting in lesser metatarsalgia and stress fractures (Ford & Gilula, 1977; Mann et al., 1979; Smith et al., 1987). As with hallux valgus, the modified Keller arthroplasty, without joint implant, is best reserved for older, less active patients with significant degenerative joint disease of the first metatarsophalangeal joint.

2.4.2.3 Arthrodesis of first metatarsophalangeal joint

Arthrodesis of the first metatarsophalangeal joint was first described by Clutton in 1894 (Bouchard & Adad, 1996), and is designed to eliminate joint pain while maintaining forefoot stability and reducing the incidence of post-operative lesser metatarsalgia (Smith et al., 1987). The procedure is advocated for patients with advanced osteoarthritic changes to the joint, in whom joint reconstructive procedures are contraindicated, or other procedures have failed (Smith et al., 1987; Chang, 1996; Bouchard & Adad, 1996).

The main limitations of the procedure are that an extended period of non-weight bearing is required, hence the surgery may only be performed unilaterally. In addition, it is not possible to perform the surgery in the presence of osteoporotic bone, often seen in elderly patients. Post-operatively, the patient's heel height must be restricted or they may be prone to develop arthritic symptoms at the interphalangeal joint of the hallux.

2.4.2.4 Osteotomies of the hallux and first metatarsal

Dorsal wedge osteotomy of the base of the hallux has been described to decompress the first metatarsophalangeal joint and create a rocker-bottom effect (Kessel & Bonney, 1958; Moberg, 1979). This procedure has been credited with reasonable long-term results for patients with adequate pre-operative dorsiflexion (Southgate & Urry, 1997). In a similar fashion, an enclavement procedure to shorten the hallux has been described (Regnauld, 1986), with generally favourable results being reported (Quinn et al., 1990).

Osteotomy of the first metatarsal allows for plantar flexion and/or shortening of the metatarsal, decreasing retrograde forces of the hallux on the first metatarsal head to potentially increase the range of motion of the joint and reduce pain (Smith et al., 1987; Chang, 1996). Various distal metatarsal osteotomies have been outlined, including the Waterman procedure, a dorsal wedge osteotomy of the head of the first metatarsal (Carvolo et al., 1979; DeLauro & Positano, 1989), and a modified version or Green-Waterman osteotomy, to preserve the plantar aspect of the first metatarsal (Smith et al., 1987). Similarly, a number of proximal osteotomies including the oblique closing base wedge, Juvara and the sagittal Scarf procedures have been developed and may best be employed to plantar flex an extremely elevated first metatarsal (Chang, 1996). The disadvantage of the Waterman-type osteotomy is that they provide for shortening but not plantarflexion of the metatarsal.

Proximal osteotomies of the first metatarsal such as the sagittal "Z" or Scarf osteotomy may be used with good effect to plantar flex, and if necessary, shorten the first metatarsal, however they require an extended period of non-weight bearing, permitting unilateral surgery only (Chang, 1996).

The Youngswick modification of the Austin bunionectomy was first described in 1982, and consists of transverse "V" metaphyseal osteotomy, with an additional osteotomy parallel just proximal to the dorsal arm of the initial osteotomy (Youngswick, 1982). By removing the resultant dorsal wedge of bone, the metatarsal head may then be re-positioned onto the proximal surface of the metatarsal, resulting in relative shortening and plantarflexion of the metatarsal head. See Figure 2.7. Youngswick (1982), reported on the short to medium term results of the operation on ten feet, maintaining overall good results with the only complications being two cases of delayed healing. A detailed

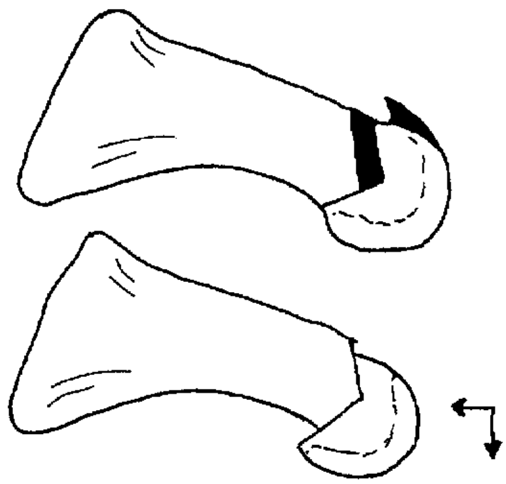

Figure 2.7 Diagrammatic representation of the Youngswick first metatarsal osteotomy

description of the Youngswick modification of the Austin bunionectomy, as performed on subjects in this study, appears in Appendix B.

Relatively little research has been conducted to investigate changes in foot function following surgery for hallux limitus. Despite the apparent contemporary popularity of the Youngswick procedure, no research other than Youngswick's original paper, has been published on the operation. In this respect, there exists an obvious need to investigate the effects of the Younsgwick procedure on foot function as measured by plantar pressure distribution.

2.5 The Development Of Plantar Pressure Measurement Systems

2.5.1 Instrumented shoe

The earliest studies to investigate dynamic foot-to-ground contact relate to the work of Carlet in 1872 and Marey in 1873 in Paris, and date back to the last quarter of the 19^{th} century (Alexander et al., 1990). These early investigations used specially constructed shoes with air chambers in the soles connected by hoses to recording equipment - an innovative, but cumbersome attempt to objectively record foot contact during gait.

In more recent times, a device consisting of spring elements instrumented with strain gauges was used under the forefoot and heels of shoes, to measure vertical ground reaction and shear forces (Spolek & Lippert, 1976). A notable feature of this instrument was the obtrusive nature of the device and its potential to alter a subject's gait. A similar, although less cumbersome device was tried subsequently, consisting of strain gauges fixed between a metal plate and the sole of the test shoe (Miyazaki & Iwakura, 1978). This device produced variable transducer sensitivity with different foot types and shoe rigidity, and lead to marked subject awareness of the test shoe.

A few years later, in an attempt to improve the practical aspects of the device, an instrument was produced with two large capacitance transducers per shoe (Miyazaki & Ishida, 1984). The main drawback of this device was its ability to measure only total vertical force. More recently, a sole was devised with multiple 8mm thick triaxial load cells which could record sequential steps and centre of pressure (Ranu, 1986). Again, as with all of these examples of early attempts to measure foot pressures, the device was large and cumbersome, limiting its clinical and research potential.

2.5.2 In-shoe transducers

Thin small disc-like transducers applied within the shoe have been developed to measure dynamic foot pressures. The two basic types of in-shoe transducers include capacitance and conductive transducers.

2.5.2.1 Capacitance transducers

These consist of two metal plates separated by a deformable medium, which when pressure is applied, causes a decrease in the metal separation, altering the electrical capacitance of the device and therefore the electrical output.

Schwartz and Heath, in the 1930's, developed six small pressure-sensitive disc-like pads, taped to the plantar aspect of the foot, allowing bare foot and shod measurements to be made. The system recorded pressure as a function of time, and the authors described the resultant output as 'electrobasographic records', involving the use of light prisms and

galvanometer mirrors linked to the transducers to expose images on a moving roll of photographic paper (Schwartz & Heath, 1937; cited in Alexander et al., 1990). Although good accuracy and reproducibility was claimed, the device was abandoned due to technical difficulties related to the complexity of the system (Alexander et al., 1990).
Almost thirty years later, Bauman and Brand (1963), used 1mm thick transducers with $1cm^2$ pressure sensitive area, taped to the hallux, first, second, fifth metatarsal heads and central heel of patients with neuropathic ulcers to measure pressure over time. A junction box connecting the transducers was joined to a preamplifier via a 4.5m cable. As with previous attempts, the device was somewhat cumbersome and had to be calibrated with each trial, due to the sensors being extremely temperature sensitive (Bauman & Brand, 1963; cited in Alexander et al., 1990).

2.5.2.2 Conductive transducers

With conductive transducers, deformation of a portion of the device results in a change in resistance of the transducer, leading to alteration of voltage output which may be related to pressure through appropriate calibration and modification of the signal. Lereim and Serck-Hanssen (1973), used a transducer of a similar type. They employed a 2.5mm thick silicone membrane housed in the sole of a test shoe, which produced a change in electrical current with deformation of the membrane. The literature records no clinical studies of their work, so an evaluation of the usefulness of their technique cannot be made.

A similar but lower profile device, only 0.9mm thick and made from beryllium copper was later developed (Somes et al., 1982). Fifteen separate sensors, each a 3x5mm strain gauge cantilever beam, were individually placed beneath radiographically defined areas of the foot. While the accuracy and reproducibility of the device was said to be good, accurate placement of the sensors was rather time-consuming and shoe variables limited the usefulness of the equipment (Alexander et al., 1990).

Other devices have been tried, including a transducer consisting of two rigid brass plates separated by a core of carbon impregnated polyurethane foam (Shereff et al., 1985). The major limitation of this equipment was an inability of the device to differentiate between horizontal and vertical forces. A completely different type of transducer, consisting of a piezoelectric crystal embedded in epoxy resin has also been described (Hennacy & Gunther, 1975). Calibration of this device demonstrated a linear transducer reaction to applied force, although no clinical trials were ever reported using this equipment (Alexander et al., 1990).

Transducers able to measure shear forces have been reported, consisting of two small metal discs separated by a layer of silicone rubber (Pollard et al., 1983). A semi-conductor field coil was mounted on one disc with a magnet attached to the opposite disc. By altering the orientation of the two discs, measurement of transverse and horizontal shear as well as vertical force could be achieved. In this study the device showed clinical potential by enabling comparison of forces under the hallux, metatarsal heads and heel with various shoes, insoles and plaster cast immobilisation. The study concluded that plaster casts reduced all three types of forces measured to a greater extent than did footwear with or without insoles, thus providing a mechanical explanation of the healing of neuropathic ulcers in plaster cast therapy.

More recently, the F-Scan® insole, an in-shoe system of pressure measurement has become commercially available. The insoles consist of a grid-work of 960 ink-filled contact points <60 μm thick, embedded in a 0.18mm thick layer of Mylar substrate (Ahroni et al., 1998). As pressure is applied, the conductive particles within the ink are brought closer together, reducing the electrical resistance within the field. While Ahroni et al. (1998), reported the pressure measurements obtained from the F-Scan as being generally reliable, the accuracy and reliability of the F-Scan insoles with repeated use have been criticised by other researchers (Rose et al., 1992; Cavanagh, 1995; Brown et al., 1996). Although the use of the F-Scan has been suggested as a means of accurately assessing foot function and treatment in podiatry (Young, 1993; Pitei et al., 1999), the sensor system has been found to be sensitive to surface conditions, loading speeds and temperature and not suitable for accurate dynamic measurements (Luo et al., 1998; Sumiya et al., 1998).

2.5.3 Floor mounted devices

2.5.3.1 Printing techniques

The earliest attempts to record pressure patterns of the foot during gait were modeled from observing footprints left in the sand or mud (Betts et al., 1991). Various experiments involved subjects walking over layers of plaster of paris covered with cloth, or using ink and paper techniques, and even having subjects walk over layers of lead shot wedged between a steel base-plate and a thin covering of lead sheet.

Using the ink and paper model, Morton introduced a 'kinetograph' in 1935, consisting of a rubber sheet with triangular ridges on its undersurface, producing an inked print of a subject's foot on paper, with the density of lines produced, being somewhat proportional to the pressure (West, 1987). Harris and Beath introduced a mat devised on this principle in 1947, which is often historically referred to in the literature (Silvino et al., 1980; West, 1987, Welton, 1992). The undersurface of the Harris and Beath mat had ridges at differing heights, giving an increased density of the print proportional to pressure, producing a somewhat accurate but purely qualitative impression of foot pressures.

A modern version of the Harris and Beath mat, the 'Podotrack®', has been tested against an optical pedobarograph, and described as a simple inexpensive semi-quantitative footprint mat, suitable as a screening device to identify areas at risk of ulceration in diabetic patients (van Schie et al., 1999).

2.5.3.2 Optical techniques

In 1934, Elftman developed an instrument consisting of a black rubber mat with pyramidal projections on its underside, and a thin layer of white fluid between the mat and the supporting thick glass plate (Alexander et al., 1990). A motion picture camera producing a slow motion image was mounted underneath the glass plate to record the visual contrast between the black mat and the deforming white fluid. High pressure areas appeared darker on film than light pressure areas, again producing a qualitative

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impression of foot loading pressure during the stance phase of gait (Alexander et al., 1990). This principle was improved by Barnett in 1954 and Simkin and Stokes in 1982, but since each of these authors produced only qualitative results, the principle has proved useful only for making general comparisons between subjects (West, 1987).

The introduction of modern computer processors and microchip technology has lead to the development of increasingly sophisticated force plates, critical light reflection techniques and improved transducer matrices. This technology has allowed plantar pressure measurements to become both qualitative and quantitative in their nature.

2.5.4 Force plates

The introduction of the first modern force plate is attributed to Cunningham and Brown in 1952 (West, 1987). This consisted of strain gauges mounted on four aluminium columns, which could measure force as well as the coordinates of the instantaneous centre of pressure. More recently, a similar arrangement was developed which was able to measure vertical forces together with fore-aft and medial-lateral shear forces, permitting the concept of force-time-impulse to be described as a measure with potential clinical application (Katoh et al., 1983).

Kistler force plates have been commercially available for nearly three decades, and are based on piezoelectric quartz transducers that are sensitive to loads in three orthogonal directions (Vaughan et al., 1992). Such force plates are well regarded for their accuracy in measuring ground reaction forces (Cavanagh & LaFortune, 1980), however they provide no information regarding the distribution of force (i.e. pressure), without time-consuming spatial analysis (Cavanagh & Ae, 1980).

2.5.4.1 Critical light reflection technique

The critical light reflection technique was first decribed by Chodera and Lord (1979), and was further modified and improved by various researchers (Betts et al., 1980a; Betts et al., 1980b; Duckworth et al., 1982; Duckworth et al., 1985; Franks et al., 1983). The systems have in common, a deformable plastic sheet over a transducer-mounted glass plate illuminated from the side, with a video recorder and microcomputer. As the foot deforms the plastic sheet the intensity of the light emitted at the site of contact is proportional to the pressure, except at extreme pressures (Alexander et al., 1990). This system has the advantage over earlier force platforms of being able to measure pressure-time-integrals.

2.5.4.2 Floor mounted transducers

As force plate technology evolved, devices were designed and constructed to allow for quantitative and qualitative measurements of parameters such as peak pressure at specific sites of the foot. Hutton and Drabble (1972) and Marey and Solomon (1979), reported on the design of platforms using strain gauges with beams oriented transversely or longitudinally to the walkway, combined with inking or photographic techniques respectively, to determine foot position. Unfortunately, the small size of the platform used necessitated the re-composition segmented foot strikes to represent an entire foot plant. This required smoothing of the force/time curves, increasing the potential error of measurement (Alexander et al., 1990). The latter platform was described as having wide clinical application, however, pressure areas were calculated from transverse sections of the foot with poor correlation with specific anatomical landmarks (Dall, 1984).

Another floor mounted transducer matrix was described in a study of hallux valgus feet by Hutton and Dhanendran (1981). The system consisted of a contact area of 1.5 x 1.5cm load cells, each made of a stainless steel ring attached to four strain gauges. As with many of the earlier platforms, foot position over the sensors was assessed via a fabric-ink-paper technique. The system suffered from inaccuracy of measurement due to a variety of causes, including the relatively large sensor area, and most notably, from a lack of positioning accuracy of the sensors over defined areas of the foot (Hutton and Dhanendran, 1981).

A third type of floor mounted system, the Musgrave pressure plate system (WM Automation and Preston Communications Ltd, North Wales, UK), has been described by Kaliszer et al., (1989), as fixed pressure plates constructed from arrays of load cells, interfaced to a BBC computer. Kaliszer et al., (1989), described the main advantages of the Musgrave system as its ability to measure and analyse spatial distributions of contact pressures versus time, being relatively inexpensive and useful in the clinical setting. The authors indicated that the main disadvantage of the system was the potential disruption of the subject's natural gait pattern with the need for accurate foot placement due to the relatively small size of the platform. In a study of 100 normal feet using the Musgrave system, significant differences in most pressure parameters, including peak pressure, contact time and contact area, were found between left and right feet (Kaliszer et al., 1989), suggesting questionable reliability of the system.

An early precursor to the present day EMED-SF systems was a portable capacitance mat, consisting of an upper layer of conductive plates arranged in rows and a lower layer joined in columns, each separated by an elastic rubber material (Hennig & Nicol, 1978; Nicol & Hennig, 1978). The transducers were linked to light emitting diodes (LEDs), the brightness of which was proportional to the force applied. Unfortunately, the system suffered from poor resolution due to transducer size, a low sampling rate of 25Hz, poor correlation between foot image and transducer location and limited accuracy of measurement (Alexander et al., 1990). The system however, is relatively inexpensive to construct, and in contrast with most systems previously described, had the benefit of being portable.

This system was extensively modified, improved and marketed in 1985 as the EMED-F System (Novel Inc., Munich, Germany), following research funded by a grant from the German Ministry of Technology (Alexander et al., 1990). The number and density of sensors, sampling rate, sensor resolution, accuracy of measurement and hysteresis, have all been markedly improved over earlier force platforms, to the point where the EMED Systems produce accurate and reliable results (Alexander et al., 1990; Graf, 1993; Hughes et al., 1991; Bryant et al., 1999a). The same sensor apparatus is also available embedded in 2mm thick flexible shoe inserts, permitting in-shoe plantar pressure measurements to be made (Graf, 1993). This important innovation has been successfully used in clinical research for assessing the effects of footwear or orthotic design on plantar pressures (Sanfilippo et al., 1992; Lemmon et al., 1997; Cornwall & McPoil, 1995; Cornwall & McPoil, 1997). However, the in-shoe EMED System has fewer sensors per cm^2 than the floor mounted system, limiting its topographical accuracy.

From the description of the evolution of pressure measurement equipment, it is apparent that modern computerised techniques with the capacity to produce accurate and reliable spatially and time oriented force/area measurement parameters have only been available for use in relatively recent times. Previous plantar pressure distribution studies of the foot have been conducted using a wide variety of equipment and measurement techniques, producing questionable results. Therefore, an obvious need exists to conduct plantar pressure distribution studies using a modern computerised force platform, such as the EMED-SF system, in normal subjects and in those with foot pathology.

2.5.2 Reliability Of Plantar Pressure Measurements Using The EMED System

The main technologies for plantar force or pressure distribution measurements include piezo-electric methods, strain gauges, optical methods, resistive methods and capacitive methods (Morlock, 1991). Accordingly, measurements using different contemporary equipment may vary as much as 10%, which may be acceptable clinically in certain situations, but such variation of measurement is not necessarily acceptable for research purposes (Hughes et al., 1991). The reliability and reproducibility of any pressure recording system used in research must, of necessity, be of a high standard.

The recording of plantar pressure measurements using the EMED-F system, a precursor to the system used in the present study, has been found to offer a good level of reliability for most force/pressure variables for repeated recordings (Hughes et al., 1991). However, when the mean result of three or more trials were used, the reliability was found to be excellent, with correlation coefficients at most sites of the foot tested of 0.75 to 0.90. Hughes et al. (1991), maintained that 100% reliability cannot be expected when measuring variables connected with gait, as gait is a learned process and is known to vary slightly between walks and between subjects.

The characteristics of the capacitive sensors used in the EMED systems are such that the hysteresis or distortion of the signal due to pressure or friction at the foot-sensor interface is reported to be less than 3% (Graf, 1993; Morlock, 1991), with an overall accuracy of measurement of about 5% (Morlock, 1991). McPoil et al. (1995) and Kernozek et al. (1996), also investigated the reliability of the EMED sensors used in the Pedar in-shoe pressure measurement system, and found them to produce reliable and reproducible pressure recordings.

In summary, the reliability of measurement of the EMED systems has been demonstrated to be good, in the clinical setting the intra-subject reliability of the system is of paramount importance. This has not been previously reported and therefore is in need of examination.

2.6 FACTORS INFLUENCING PLANTAR PRESSURE DISTRIBUTION

2.6.1 Subject demographics

Subject demographic characteristics such as gender, age and body weight have been investigated to assess their influence on plantar pressure distribution. With respect to gender, the literature suggests no significant differences exist between male and female subjects (Soames, 1985; Shorten et al., 1989; Bennett & Duplock, 1993; Hennig et al., 1994).

Although body weight and body stature have been reported to effect kinetic measurements of gait (Hof, 1996), and severe obesity to influence foot mechanics during walking (Messier et al., 1994), no relationship has been demonstrated between peak foot pressures and body weight in normal subjects (Hennig & Rosenbaum, 1991). Similarly, other researchers have reported poor correlation between body mass and peak plantar pressures (Cavanagh et al., 1991). Cavanagh et al. (1991) compared pressure measurements of 56 diabetic men and a similar number of control subjects using an optical pedobarograph, concluding that foot structures (bony prominence) were implicated in the production of elevated plantar pressures, rather than body weight.

The influence of age on plantar pressure distribution has received little attention in the literature. Hennig and Rosenbaum (1991), investigated the differences in peak pressures between 15 young children with a mean age of 23.5 ± 5.7) months and 111 adults with a mean age of 27.4 ± 8.4) years, using an EMED system. They found mid foot pressures in the children studied to be almost three times higher than in the adult group, suggesting that the immature foot has a weak arch structure. As the children's age increased, the plantar distribution tended to resemble that of the adult foot-loading pattern.

In a similar study, Hennig et al. (1994) compared plantar peak pressures in 125 children with a mean age of 8.5 ± 1.1 years with 111 adult controls with a mean age of 27.4 ± 8.4 years. They found reduced peak pressures under all sites tested in children, compared with adults, which they ascribed to the relatively larger feet seen in growing children, and therefore greater surface area. With increasing age, medial loading was noted to increase slightly in the children. This finding is in keeping with Kernozek and LaMott (1995), who found increasing medial loading with age, while comparing 35 subjects with a mean age of 78 ± 3.0 years with 35 subjects with a mean age of 22 ± 2.2 years.

2.6.2 Subject kinematics

Walking speed has been demonstrated to alter the kinematics of gait (McCullock et al., 1993) and to directly increase the magnitude of peak forces measured under the foot (Shorten et al., 1989; Hughes et al., 1991; Rosenbaum et al., 1994; White et al., 1996). Rosenbaum et al. (1994), also reported a significant increase in peak pressures beneath the heel and medial forefoot with increasing walking speed.

2.6.3 Subject foot characteristics

Interference with normal sensory input, as a result of disease, injury, or other causes, may produce an alteration in posture and the kinematics and kinetics of gait, and has been demonstrated to influence plantar pressure distribution (Chen et al., 1995). Indeed, there is speculation that sensory input concerned with the maintenance of comfort and stability of the foot is associated with plantar pressure distribution, and in particular, with pressure-time-integrals (Chen et al., 1995).

The relationship between foot morphology and plantar pressure distribution has been studied with interesting results. Walker and Fan (1998), used a pedobarograph to assess peak plantar pressures under the feet of 54 adults, whose feet were classified into normal, pronated and supinated groups. They found no significant relationship between foot type and peak pressure distribution. Similarly, Rosenbaum et al. (1994), found no relationship between low, medium and highly arched feet in 30 healthy subjects.

The association between foot structure and peak plantar pressure measurements has been investigated with varying results. Cavanagh et al. (1997) reported a weak association between certain foot radiographic measurements and plantar pressure measurements of the heel and first metatarsal head in 50 normal subjects, particularly related to the thickness of the plantar skin beneath these osseous landmarks. This view is supported by the findings of Jahss et al. (1992). Morag and Cavanagh (1999), using an EMED SF2 system, obtained plantar pressure measurements from four sites of the foot of 55 normal subjects. They compared these with weight-bearing radiographic measurements, range of motion of the ankle and first metatarsophalangeal joints, and electromyographic measurements of certain extrinsic foot muscles. Morag and Cavanagh (1999) reported that approximately 50% of the variance in peak pressure might be attributed to foot structure and function. In particular, foot structure was related to peak pressure under the mid-foot and first metatarsal head, while structure and function was associated with the heel and hallux.

With respect to the relationship between osseous foot structure and plantar pressure distribution, the paucity of literature available demonstrates a lack of consensus of opinion regarding this relationship. Furthermore, no research of this nature has been published investigating the relationship between foot structure and plantar pressure distribution in normal feet compared with feet with hallux valgus or hallux limitus.

2.6.4 Method of data collection

Most researchers adhere to a protocol of using a mid-gait method of data collection, where a number of strides are made before the foot strikes the recording equipment, combined with instructing subjects to avoid looking at the force platform. The use of a mid-gait method is predicated on the assumption that this technique represents a true reflection of foot function during normal gait. While instructing subjects not to look down at the force platform is designed to prevent 'targeting' in an attempt to avoid producing aberrant foot contact with the platform. However, the importance of the avoidance of platform targeting has been demonstrated not to have a significant effect on kinetic variables related to ground reaction forces (Grabiner et al, 1995; Wearing et al, 2000).

The necessity to adhere to the mid-gait method of data collection has been recently questioned. Myers-Rice et al. (1994), using an EMED SF system, investigated the reliability of pressure data collected by one-step, two-step and the more traditional mid-gait method. They recorded pressure data from only the heel, mid foot and forefoot of ten subjects and found the two-step method provided measurements of peak pressure and peak vertical force of the forefoot and rearfoot similar to those obtained from the mid-gait method. They reported less than 5% difference between measurements obtained from either technique.

The number of trials required to obtain an acceptable level of reliability of regional plantar pressure measurements with the two-step and mid-gait methods of data collection was investigated by McPoil et al. (1999). Using an EMED-SF system they examined five broad regions of the foot in ten healthy subjects using both methods of data collection. With the exception of the heel region, the mean of three trials for each subject was found to be necessary to eliminate significant differences ($p>0.1$) for contact-time, peak pressure and pressure-time-integrals. Intraclass correlation coefficients for peak pressure and pressure-time-integrals were found to be 0.975 or above when three or more trials were used, with the exception of the lateral forefoot, which was calculated to be 0.776 (McPoil et al., 1999).

The differences in peak pressure and temporal parameters between midgait, two-step gait initiation and two-step gait termination methods of data collection have recently been investigated by Wearing et al. (1999). Using an EMED-SF system and twenty-five healthy volunteers, ten trials of each subject were obtained for seven regions of the foot for each data collection method. The results demonstrated that for all three methods of data collection and for pressure variables at most sites of the foot tested, only two or three trials were necessary to produce intraclass correlation coefficients of 0.75 or more. To achieve values of 0.9 or greater, up to ten trials were required. Comparing midgait with the two-step initiation and termination methods, only contact time for the lesser digits was found to be significantly greater with the two-step initiation method compared with the traditional midgait technique (Wearing et al, 1999).

Given that the two-step method of data collection requires less space for equipment and is easier for subjects to perform, it is more amenable to the clinical setting than the traditional mid-gait technique. However, further study is required to investigate the reliability of the two-step method compared with the mid-gait technique, in particular with detailed reference to the forefoot, an area of the foot subject to considerable pathology and of significant clinical interest.

2.7 Clinical Application Of Plantar Pressure Measurement

Quantitative assessment of plantar pressure distribution has direct clinical application and provides the clinician with objective measurement parameters enabling the comparison of results with normal reference range values, and the monitoring of the effects of invasive or non-invasive treatment (Alexander et al., 1990; Morlock, 1991; Finch, 1999).

2.7.1 The diabetic and rheumatoid foot

Plantar pressure measurement techniques have been applied in the testing of shoe modifications or insoles (Lemmon et al., 1997) and foot orthoses (Birke et al., 1991; Novick et al., 1993; Albert & Rionoie, 1994; Cornwall & McPoil, 1997), particularly with regards to the diabetic foot. The assessment of plantar pressures (Takagi et al., 1998), and the effects of surgery on pressure distribution have also been investigated in the rheumatiod foot (Samnegard et al., 1990; Phillipson et al., 1994; Harris et al., 1997).

The earlier reported clinical importance of monitoring pressure distribution in the diabetic foot (Duckworth et al., 1985; Wolfe et al., 1991; Veves et al., 1992; Cavanagh et al., 1993; Caputo et al., 1994), has recently been supported by research establishing the relationship between plantar pressures and ulcer formation in the diabetic foot (Murray et al., 1996; Stess et al., 1997; Armstrong et al., 1998).

Case reports outlining the role of plantar pressure measurement in monitoring the pre- and post-operative status of patients with diabetes after metatarsal head resection (Patel & Wieman, 1994) and amputation of the hallux (Lavery et al., 1995) have been described. The influence of hallux valgus as an aetiological factor in plantar ulceration in the insensate foot has been proposed (Lavery et al., 1998), while a case study demonstrating changes to plantar pressure distribution following corrective hallux valgus surgery for plantar ulceration has been reported (Bryant et al., 1999b).

2.7.2 Hallux valgus

While hallux valgus is a relatively common condition, the relationship between plantar pressure distribution and hallux valgus has received little attention in the literature. The feet of 64 asymptomatic subjects (128 feet) were compared with those of 20 patients (34 feet) with hallux valgus, using a force platform connected to strain gauges (Stokes et al., 1979). While Stokes et al. (1979) noticed considerable variation of peak pressure distribution in the control subjects, significantly higher values were found in the medial forefoot of normal feet compared with lateral loci of peak pressure of the forefoot in hallux valgus subjects. Five elderly hallux valgus patients underwent Keller arthroplasty with silastic joint implant while fifteen younger patients were treated by the Wilson oblique sliding first metatarsal osteotomy. Repeat pressure measurements were conducted only relatively early during the recovery period, between 14-35 weeks post-operatively, showing a similar pressure distribution pattern, with increased values for both the Keller and osteotomy groups beneath the third, fourth and fifth metatarsal heads.

A similar quantitative study has been reported comparing plantar pressure measurements of 32 normal subjects (64 feet) with 34 hallux valgus subjects (65 feet), using a platform comprised of 128 load-cells with strain gauges (Hutton & Dhanendran, 1981). By dividing the foot into eight regions, they found the hallux and second toe to show significantly lower peak pressures with the third to fifth metatarsal heads demonstrating significantly higher peak pressures in hallux valgus feet compared with normal feet. Contact time-parameters showed that patients with hallux valgus had significantly longer loading times on their heel, mid-foot, and second to fifth metatarsal heads, with less time on the hallux compared with normal feet.

Hutton and Dhanendran (1981) also reported the pre-and post-operative pressure measurements made in the hallux valgus group, all of whom underwent a Keller arthroplasty procedure. Post-operatively, increased peak pressures were noted beneath the first metatarsal head with decreased pressures under the hallux and second toe. Contact times were also significantly reduced beneath all toes following surgery. While 11 of the 34 hallux valgus subjects were tested one year post-operatively, the post-operative measurement time for the remaining subjects was not reported. However, the reliability of the equipment used in this study and therefore the validity of the results obtained has been questioned (Alexander et al., 1990).

Pre-and post-operative plantar pressure changes in 36 feet, following the Wilson oblique metatarsal osteotomy, using similar equipment to that of Hutton and Dhanendran (1981) were reported by Allen et al. (1981). The authors found a lateral shift of the weight-bearing pattern in the forefoot in the first six months after surgery with less pressure on the toes, which tended to return to the pre-operative pressure distribution over the next four years.

Using an early EMED gait analysis system, Blomgren et al. (1991), compared peak pressures of 60 normal and 66 hallux valgus feet, with the foot divided into nine regions. Their results demonstrated decreased peak pressures in hallux valgus feet under the first, second, third and fourth metatarsal heads and heel, with increased pressure beneath the fifth toe and mid-foot. In this study, the pressures of a single footfall only were recorded and used in the subsequent analyses, rather than the mean recordings of a number of foot plants, which may have affected the reliability of the measurements and hence the results.

Post-operative plantar pressure of 46 patients (63 feet) undergoing an aggressive sub-capital osteotomy for hallux valgus was assessed using an EMED-F system (Wanivenhaus & Brettschneider, 1993). The surgical technique employed produced considerable lateral and plantar displacement of the first metatarsal head. "Normalisation" of pressure was said to occur beneath the second metatarsal head with increased pressure at the first metatarsal head when plantar displacement of the first metatarsal head of over 11mm was achieved. Unfortunately, pre-operative plantar pressure measurements were not recorded as a base for comparison with post-operative values, casting doubt on their findings.

A pedobarograph was used by Borton and Stephens (1994), to qualitatively assess the weight-bearing distribution in 31 hallux valgus patients (32 feet), six to nine months after a proximal Chevron first metatarsal osteotomy. They found a pre-operative trend for the centre of pressure to lie laterally through the third metatarsal head, with a change post-operatively yielding medialisation of the centre of load through the first and second interdigital space.

An EMED-SF system was used to investigate a sample of 81 normal feet and 101 hallux valgus feet, with 33 of these following either a Keller arthroplasty, a basal first metatarsal osteotomy or a corrective unspecified soft-tissue procedure (Libotte, 1994). The report is descriptive and suggests that plantar loading of the hallux is less in the hallux valgus foot and related to the hallux valgus angle. Post-operatively, load beneath the hallux in the Keller group was said to decrease, increase with the soft-tissue procedure, while loading of the central metatarsals was found to increase with the basal osteotomy. No statistical evidence supporting these findings was outlined.

The effect on plantar pressure distribution following a combined distal soft-tissue and basal first metatarsal osteotomy in 29 feet of 17 patients presented as an abstract (Nyska et al, 1994). Using an EMED system, they reported of hallux valgus feet that the hallux had reduced areas of contact, force and force-time-integral, with increased pressure-time and force-time-integrals of the mid-forefoot. Post-operatively, they reported increased contact time and force beneath the hallux and increased pressure-time and force-time-integrals of the mid-forefoot. The report failed to mention if control subjects were used, nor was any statistical evidence supplied to support their findings.

The clinical, radiographic and plantar loading effects of a sliding Wilson osteotomy for the correction of hallux valgus was reported on 17 patients, 14 months post-operatively (Toth and Fabula, 1994). An EMED-SF system was used which showed most pressure variables to decrease beneath the hallux and to increase beneath the second and third metatarsal heads post-operatively, thought to be due to shortening of the first metatarsal. The authors did not include a control group in their study and produced no statistical evidence to corroborate their findings.

The Musgrave Footprint System was used by Plank (1995), to compare the mean peak pressure differences of all metatarsal heads of the right foot of 30 normal and 15 hallux valgus subjects. He used the mean data of three separate trials of all five metatarsal heads of the right foot of each subject. He reported a medial locus of peak pressure in most of the hallux valgus group, with a significant decrease in pressure beneath the fourth and fifth metatarsal heads, increased contact time and time to peak pressure with increasing hallux abduction angles compared with the normal group.

An in-shoe F-Scan system was selected by Resch and Stenstrom (1995), to evaluate pressure differences between the feet of 14 normal subjects (28 feet) and 23 hallux valgus patients (31 feet), pre-operatively and again 25 months after surgery. The mean of three foot-strikes of each subject was used in the analysis of peak pressure distribution beneath each metatarsal head, the base of the fifth metatarsal head and the heel. The surgery performed was not standardised, consisting of either a distal Chevron osteotomy of the metatarsal head or a closing base wedge osteotomy of the first metatarsal base. Pre-operatively, they found significantly lower pressures beneath the hallux in the hallux valgus group, compared with normal, which pressures remained unchanged post-operatively. They reported higher pressures beneath the third metatarsal head in the post-operative period. The results of this study however, must be questioned as the accuracy and reliability of the calibration and stability of the F-Scan sensor insoles has been described as poor (Rose et al., 1992; Cavanagh, 1995; Brown et al., 1996).

More recently, Yamamoto et al. (1996), using pressure sensitive film, examined forefoot pressures in 32 female subjects (50 feet) with hallux valgus and 40 normal female subjects. They found increased peak pressures beneath the first, second and third metatarsal heads in hallux valgus feet. Following hallux valgus surgery in 20 feet (distal crescentic osteotomy), at an average of 26 months postoperatively, they found forefoot peak pressures were not significantly altered, remaining centered beneath the second and third metatarsal heads. The authors did not comment on the accuracy and reliability of the pressure measuring equipment used and the description of their results is largely qualitative in nature. Table 2.1 summarises reported plantar pressure trends in hallux valgus feet.

The available literature reviewed which examines plantar pressure distribution between normal and hallux valgus feet demonstrates a wide range of results, arising from considerable variation in methodology, the use of different pressure recording equipment, data collection techniques and the selection of subjects. Furthermore, only scant research has been conducted on pre-and post-operative changes to plantar pressure distribution in feet with hallux valgus. For similar reasons, the results of the few published studies are inconsistent and fuel the need for further research in this area.

Table 2.1 Reported relative magnitude of peak pressures in hallux valgus feet compared to normal feet.

Study	Hallux	T2	T3-5	1MH	2MH	3MH	4MH	5MH
Stokes et al (1979)						↑	↑	↑
Hutton and Dhanedron (1981)	↓	↓	↑			↑	↑	↑
Blomgren et al (1991)			↑	↓	↓	↓	↓	
Plank (1995)						↓	↓	
Resch and Stenstrom (1995)	↓							
Yamamoto et al (1996)			↑	↑	↑			

T2 = 2nd toe, T3-5 = 3rd-5th toes, MH = metatarsal head, ↑= increased peak pressure, ↓=decreased peak pressure

2.7.3 Hallux limitus

Pressure measurement studies on subjects with hallux limitus are reported even less frequently in the literature than those related to hallux valgus. Betts et al. (1980b), using a force platform and critical light reflection technique, in a series of case studies, described the effects on plantar pressure distribution following the surgical treatment of four patients with hallux rigidus. Two patients underwent first metatarsophalangeal joint fusion and two patients received a Keller arthroplasty, one with joint implant. Pre-operative pressure measurements were taken for only one subject, with a reported slight increase in pressure under the hallux compared with "normal". This pressure was found to dissipate following surgery with a corresponding increase in pressure beneath the second metatarsal head. The time of post-operative pressure recordings was reported for only two patients, at one year and the other at two years post-operation. The study could best be described as preliminary, offering few subjects, and was poorly designed with no control group or description of the accuracy and reliability of the measuring equipment used.

Measuring vertical force beneath the foot using the Electrodynogram System®, Dananberg (1986), proposed that functional limitation of first metatarsophalangeal joint extension is responsible for failure of resupination of the foot following forefoot contact during gait, which may lead to knee, hip or low back pain. The author provided no scientific data demonstrating either the reliability of the measuring instrument, subject demographics or analysis of these data to support his hypothesis.

Also using an Electrodynogram System, Stuck et al. (1988), compared pre-and post-operative plantar pressure measurements, at three, six, and nine months, of five patients undergoing first metatarsophalangeal joint arthroplasty with total joint implant for the surgical treatment of hallux limitus. They reported a significant mean reduction in contact time of the hallux in four of the five patients post-operatively. In addition to the small sample size, the authors failed to report a detailed account of their methodology, the reliability of the measuring equipment or the results of any other force parameters measured.

An EMED system was used by Samnegard et al. (1991), who examined 20 patients whom had previously undergone surgery for the correction of hallux limitus deformity compared with 10 normal subjects. Ten of the surgical subjects had undergone a Keller arthroplasty and were tested an average of four years post-operatively, while the remaining surgical subjects underwent a first metatarsophalangeal joint fusion, and were tested an average of five years following operation. Samnegard et al. (1991), reported that while peak pressures beneath the hallux in the Keller arthroplasty group were lower than the other two groups, this finding was not statistically significant.

However, significantly higher peak pressures in both surgical groups for the mid-foot and beneath the first and third metatarsal heads in the arthrodesis group were reported by Samnegard et al. (1991). Unfortunately, while the authors used reliable pressure recording equipment and investigated nine regions of each foot, they used the highest peak pressure recorded during three trials for each region in the analyses, rather than the

® The Langer Biomechanics Group, Deer Park, N.Y mean peak pressures of a number of recordings. A further and more serious criticism of the study was that pre-operative pressure measurements were not recorded hence a comparison of pre- and post-operative findings could not be made.

The long term results of the surgical treatment of hallux limitus by dorsal wedge osteotomy of the hallux in 10 patients and first metatarsophalangeal joint arthroplasty in 20 patients, an average of twelve years post-operation has been reported (Southgate & Urry, 1997). Using a Musgrave force platform system, a single representative foot-plant was selected from a minimum of six trials and used for analysis of peak pressure and contact time of the hallux, first and fifth metatarsal heads. These authors reported a significant increase in duration of loading of the fifth metatarsal head in the arthrodesis group and an increase in peak pressure beneath the first metatarsal in the osteotomy group. Unfortunately, the poor methodology and design of this study precluded the comparison of pre- and post-operative data, and the reliability of the Musgrave system has previously been questioned (Kaliszer et al., 1989).

With respect to the review of the available literature, published research into plantar pressure distribution in feet with hallux limitus following surgical intervention, are very few in number with inconsistent results, demonstrating an obvious need for further research in this area.

2.8 Summary

Hallux valgus or 'bunion deformity' is a structural deformity of the first metatarsophalangeal joint of the foot. It is a relatively common foot condition, more prevalent in women than in men and showing an increased incidence with age. The aetiology of the deformity is multi-factorial, with excessive foot pronation, systemic arthridites and localised structural variations thought to be the primary causes. Further investigation into the radiographic structure of the forefoot is required to improve the understanding of the underlying osseous causes of the deformity.

Hallux limitus is a related condition causing degenerative arthrosis of the first metatarso-phalangeal joint. In common with hallux valgus, the incidence increases with age, however, the condition is more prevalent in males than in females. Trauma, systemic arthridites and local structural factors are considered to be the primary aetiological factors in producing the condition of hallux limitus. The Youngswick osteotomy/cheilectomy procedure is a modification of the Austin bunionectomy and an increasingly popular operation for the treatment of grade I and II hallux limitus because of its ability to preserve the first metatarsophalangeal joint.

Plantar pressure measurement technology has evolved over the years to provide clinicians and researchers with access to data that may plausibly be applied to the study of normal and pathologic feet. Until relatively recent times, force platforms were usually found only in specialised gait laboratories or university research institutions, with most clinicians being denied ready access to the use of such equipment. With the advent of smaller, reliable and relatively cost effective computerised force platform systems, such as the EMED-SF system, endocrinologists, orthopaedic surgeons and podiatrists alike are gradually becoming aware of the potential uses of plantar pressure measurement.

There is a need to establish normal reference range values for plantar pressure measurements using the EMED–SF system where these do not exist to enable clinicians and researchers to compare data among subjects. Similarly there is a need to investigate the accuracy and reliability of using the more practicable two-step method of data collection, suitable for use in clinician offices or hospital departments, rather than the mid-gait method traditionally used in expansive gait laboratories.

Of particular interest to orthopaedic and podiatric surgeons is the effect of surgery on foot function, as assessed by plantar pressure distribution changes, following the correction of hallux valgus and hallux limitus. The available literature is virtually devoid of research describing the pressure distribution effects of the commonly performed Austin bunionectomy for the correction of hallux valgus, or the Youngswick osteotomy for the correction of hallux limitus. In this regard there is an obvious need to audit the effects of these procedures in the interests of evidence-based patient management.

CHAPTER THREE

COMPARISON OF THE TWO-STEP AND MID-GAIT METHODS OF DATA COLLECTION*

Adapted from *Bryant, A., Singer, K., and Tinley, P. (1999). Comparison of the reliability of plantar pressure measurements using the two-step and mid-gait methods of data collection. Foot & Ankle International. 20(10), 646-650.

3.0 RATIONALE OF THE STUDY

Modern plantar pressure measurement technology has the potential to provide the clinician and researcher with useful information concerning dynamic pressure distribution within the foot. The results obtained from test subjects and controls must be reliable and reproducible, capable of accurately measuring basic parameters such as area, contact time, maximum force and peak pressure. In clinical practice, the reliability of plantar pressure measurement is important when assessing changes of foot function over time or the effects of therapeutic intervention (Alexander et al., 1990).

While the mid-gait technique is an accepted protocol for studies obtaining normative data in non-pathological feet, the two-step technique may be more appropriate for certain subjects and clinical settings. For example, patients with insensate feet or those with advanced medical problems may find it difficult to complete a prolonged data recording session using the mid-gait method, and indeed, may be placed at risk of injury (Myers-Rice et al., 1994).

Subjects with significant gait or visual disturbances, or those with poor co-ordination may have difficulty stepping on the pressure platform in the required free-flowing manner which may effect the quality of data collected (Cavanagh and Ulbrecht, 1992). Furthermore, from a practical point of view, the two-step method is easier for most subjects and therefore, the time required to collect data from repeated trials of a given subject is less than with the mid-gait method.

Using an EMED SF system, Myers-Rice et al. (1994), investigated the reliability of pressure data collected by one-step, two-step and the more traditional mid-gait method. They tested 10 healthy subjects, 5 men and 5 women, with a mean age of 27 years. The right foot of each subject was divided into three broad regions, including the heel, mid-foot and forefoot. Three consecutive trials of the right foot of each subject were recorded for analysis. They found the two-step method provided measurements of peak pressure and peak vertical force of the forefoot and rearfoot similar to those obtained from the mid-gait method. The one-step method was found to produce less representative values obtained from either the two-step or mid-gait methods. They recommended using the two-step technique over the one-step technique where the mid-gait method was thought to be inappropriate.

Cavanagh and Ulbrecht (1992), outlined the importance of maintaining consistency of technique during multiple walks to increase the reliability of the results of plantar loading. Subject walking velocity, step length and cadence were identified as being important factors to consider. They suggested that for repeated trials, consistency of these factors in a given subject is more important than consistency between subjects. Test conditions must be standardised and subjects must be capable of walking in a constant manner over the measurement platform a number of times (Hughes et al., 1991).

The effect of walking speed on plantar pressure distribution was investigated by Rosenbaum et al. (1994). They reported a significant increase in peak pressure under the heel and medial forefoot, and a significant decrease under the mid-foot and lateral forefoot with increasing walking speed. Hughes et al. (1991) found that in general, total force and peak pressure increases linearly with speed, while the lateral forefoot and fifth toe areas decreased in a similar fashion with increasing speed.

The reliability of plantar pressure measurements using the EMED-F system, a precursor to the system used in the present study, was investigated by Hughes et al. (1991). Using the mid-gait technique, measurements of 12 regions of the right foot of 10 subjects were recorded which demonstrated that a reasonable level of reliability was achieved for most force/pressure variables using a single recording. However, when the mean result of three or more trials was used, the reliability was found to be excellent, with correlation coefficients at most sites of the foot tested of 0.75 to 0.90. They maintained that because gait is learned and is known to vary slightly both between walks and between subjects, a reliability of 100% cannot be expected when measuring any variable connected with gait (Hughes et al., 1991).

The purpose of this study was to compare the reliability of selected plantar pressure measurements, including contact area, contact time, maximum force and peak pressure, in seven regions of the foot from repeated trials of 30 normal subjects using the two-step and mid-gait methods of data collection.

3.1 METHOD

3.1.1 Subjects

Thirty healthy volunteers (18 females and 12 males) with a mean age of 39.8yrs (23-68yrs), mean weight of 70.1kg (48.5-96.6kg) and mean height of 168.7cm (156-185cm). All subjects were screened for obvious foot or gait abnormalities and had no history of foot or lower limb pathology in the preceding 12 months. Written consent was obtained from each subject (see Appendix D), with approval of the Human Research Ethics Committee of Curtin University of Technology.

3.1.2 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

3.1.3 Procedure

Each subject was allowed familiarisation with the testing procedure by walking over the platform at their own self-selected comfortable pace several times. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Ten subjects had data collected from both feet with the two-step and mid-gait methods on the same testing session, while data of the left foot was collected from a further 20 subjects.

For the mid-gait method, each subject's starting position was adjusted to allow for a minimum of five strides before reaching the platform. Several trials of each foot were then collected for each subject, and after discarding any aberrant footfalls, three were selected for further analysis.

Similarly, for the two-step method, each subject's starting position was determined such that the subject commenced walking with the opposite foot to that being tested, with the test foot making contact with the platform on the second step from the starting position.

3.1.4 Data and Statistical Analysis

The foot of each subject was divided into 10 regions or masks using the EMED Automask software.® Masks for the heel, first-fifth metatarsal heads and the hallux were selected for analysis. Contact area, contact time, maximum force and peak pressure for the various masks were then generated and transferred to a spreadsheet for statistical analysis using SPSS.

Intraclass correlation coefficients (ICC's) for both methods of data collection were calculated from plantar loading measurements of three footfalls of both feet of 10 subjects at all regions of the foot selected. Significant differences between the two data recording techniques for contact area, contact time, maximum pressure and peak pressure, a one-way analysis of variance (ANOVA) was employed, using data from the left feet of 30 subjects at a significance level of 0.05.

3.2 RESULTS

Intraclass correlation coefficients were generated for the seven sites examined for the mid-gait and two-step methods of data collection. Essentially, the results were similar for both feet, although the left foot demonstrated slightly more consistent results than the right foot. In general, data obtained from the two-step method were found to be more reliable than that obtained from the mid-gait technique. Refer to Table 3.1.

With respect to contact area, the reliability of both data collection methods was found to be good (≥ 0.6) to excellent (≥ 0.75), with the exception of the fifth metatarsal head with the two-step technique, in accordance with Portney and Watkins (1993). Contact time produced less favourable results with the heel and hallux producing poor results (<0.6) with both techniques, and the first-fourth metatarsal heads using the mid-gait method.

Maximum force similarly produced varying results with the heel, third and fourth metatarsal heads producing poor results with the mid-gait technique, and the first, second and fifth metatarsal heads with the two-step method. Peak pressure however, produced more consistent results with only the heel and first metatarsal head giving poor reliability with the mid-gait technique. Figure 3.1 shows the relative ICC values for contact area (cm^2), contact time (milliseconds), maximum force (% body wt) and peak pressure (N/cm^2).

The descriptive statistics and results of a one-way analysis variance of the left foot of 30 control subjects comparing the mid-gait and two-step methods of data collection are presented in Table 3.2. With the exception of the metatarsal heads for contact time,

Table 3.1 Intraclass correlation coefficients for mid-gait and two-step data collection methods of left and right feet of 10 subjects.

	Left foot		Right foot	
Contact area	mid-gait	two-step	mid-gait	two-step
Heel	0.90**	0.98**	0.99**	0.99**
MH1	0.95**	0.96**	0.92**	0.94**
MH2	0.93**	0.85**	0.88**	0.96**
MH3	0.91**	0.85**	0.83**	0.96**
MH4	0.74*	0.83*	0.44	0.92**
MH5	0.69*	0.47	0.91**	0.82**
HX	0.76**	0.85**	0.90**	0.85**
Contact time				
Heel	0.18	0.45	0.40	0.53
MH1	0.58	0.75**	0.64*	0.77**
MH2	0.53	0.69*	0.56	0.80**
MH3	0.41	0.68*	0.62*	0.82**
MH4	0.53	0.76**	0.51	0.84**
MH5	0.67*	0.71*	0.46	0.46
HX	0.43	0.42	0.47	0.58
Maximum force				
Heel	0.35	0.88**	0.54	0.87**
MH1	0.60*	0.57	0.73*	0.52
MH2	0.65*	0.58	0.60*	0.41
MH3	0.29	0.68*	0.36	0.35
MH4	0.15	0.68*	0.55	0.65*
MH5	0.68*	0.59	0.65*	0.71*
HX	0.78**	0.89**	0.69*	0.90**
Peak pressure				
Heel	0.56	0.89**	0.52	0.92**
MH1	0.47	0.73*	0.70*	0.66*
MH2	0.96**	0.89**	0.97**	0.92**
MH3	0.93**	0.97**	0.89**	0.89**
MH4	0.82**	0.94**	0.72*	0.81**
MH5	0.91**	0.95**	0.91**	0.74*
HX	0.73*	0.85**	0.83**	0.83**

MH = metatarsal head, HX = hallux, **Excellent reliability (≥0.75), *Good reliability (≥0.60)

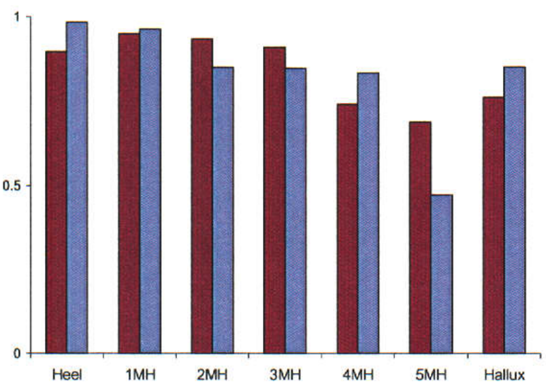
no significant differences of plantar loading variables tested could be demonstrated between the two data collection methods.

Table 3.2 Descriptive statistics and one-way ANOVA results comparing mid-gait and two-step data collection techniques of 30 subjects.

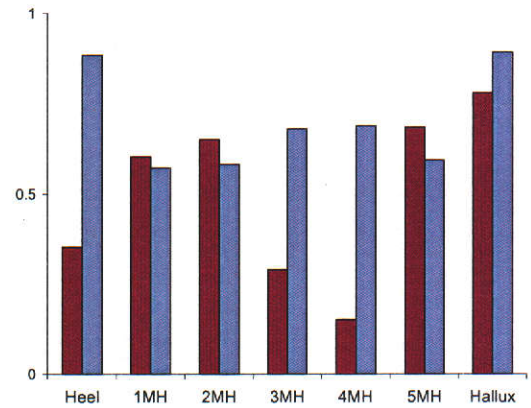
		Midgait mean [SD]	Two-step mean [SD]	F(1,59)	*P*
Contact area (cm^2)	Heel	40.70 [7.08]	43.77 [6.87]	2.90	0.094
	MH1	15.08 [3.19]	16.22 [2.62]	2.29	0.135
	MH2	12.16 [2.63]	12.73 [2.43]	0.76	0.386
	MH3	13.82 [2.35]	14.49 [1.18]	1.53	0.221
	MH4	12.14 [1.35]	12.77 [1.17]	3.70	0.059
	MH5	8.05 [1.18]	8.09 [0.88]	0.03	0.868
	HX	11.41 [1.22]	12.31 [1.60]	6.08	0.017
Contact time (msec)	Heel	408.00 [62.06]	414.00 [61.73]	0.14	0.709
	MH1	598.67 [39.28]	631.33 [51.64]	7.60	0.008*
	MH2	618.00 [38.63]	645.33 [48.69]	5.80	0.019*
	MH3	628.67 [37.11]	661.33 [50.08]	8.24	0.006*
	MH4	615.33 [35.89]	646.00 [42.07]	9.22	0.004*
	MH5	562.00 [44.37]	594.67 [34.01]	10.24	0.002*
	HX	551.00 [80.36]	566.00 [93.83]	0.44	0.509
Maximum force (% body wt)	Heel	80.56 [7.81]	78.92 [10.47]	0.47	0.497
	MH1	24.01 [4.94]	26.57 [6.00]	3.05	0.086
	MH2	26.12 [3.20]	26.44 [4.10]	0.12	0.734
	MH3	25.13 [4.09]	26.03 [5.49]	0.51	0.477
	MH4	15.09 [3.06]	15.89 [3.26]	0.96	0.331
	MH5	6.96 [2.20]	6.95 [1.75]	0.01	0.978
	HX	23.94 [8.16]	21.32 [6.85]	1.82	0.182
Peak pressure (N/cm^2)	Heel	39.52 [10.47]	35.10 [7.03]	3.68	0.060
	MH1	33.48 [15.81]	32.52 [9.31]	0.08	0.774
	MH2	45.58 [20.73]	45.22 [21.73]	0.01	0.994
	MH3	41.13 [17.71]	41.93 [18.24]	0.03	0.860
	MH4	25.98 [11.87]	27.25 [11.35]	0.18	0.674
	MH5	17.30 [14.78]	17.55 [12.52]	0.01	0.944
	HX	53.13 [16.69]	44.58 [21.23]	3.01	0.088

MH = metatarsal head, HX = hallux

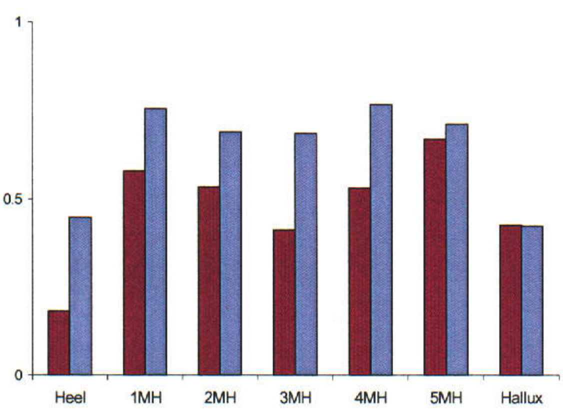
The results indicate that overall the results obtained from the two-step technique were more consistent than those obtained by the mid-gait method. Therefore, the research hypothesis that the two-step method of data collection produces data as reliable as the traditional mid-gait method is accepted.



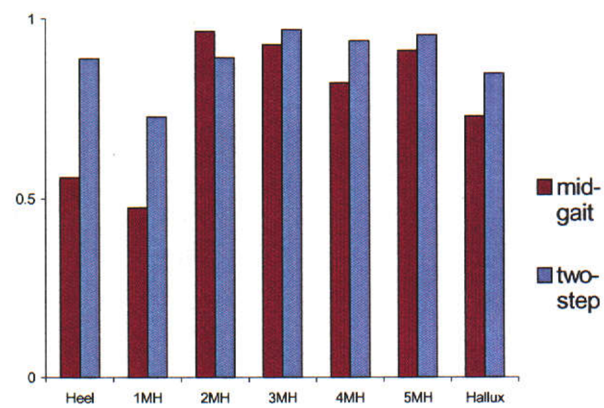
[A] Contact Area



[C] Maximum Force



[B] Contact Time



[D] Peak Pressure

Figure 3.1 Relative intraclass correlation coefficient values of plantar pressure measurements of the heel, metatarsal heads (1-5 MH) and hallux, for midgait and two-step methods.

3.3 DISCUSSION

The reliability of contact area measurements at most sites of the foot tested, for both the mid-gait and two-step methods, was found to be excellent, with the exception of the fifth metatarsal head. In general, ICC values for the two-step method of data collection were higher than with the mid-gait technique.

Contact time, however, produced less consistent results, which is consistent with the findings of Hughes et al. (1991) and Kernozek and LaMott (1995), who investigated the reliability of an EMED in-shoe system. This suggests that the reliability of contact time and derived values such as instant of peak pressure and force, at certain sites of the foot, may be less than ideal. Again, considerably better ICC values were obtained for the two-step method, with most sites of the foot giving reliability levels greater than 0.6, compared with the mid-gait technique, most sites achieving scores less than 0.6.

The reliability of maximum force was found to be poor for most sites of the foot for the mid-gait technique, with the exception of heel, third and fourth metatarsal heads. While for the two-step method, the reliability was found to be good to excellent at most sites, except for the first, second and fifth metatarsal heads. Similarly, the two-step method produced higher ICC values overall than the mid-gait technique.

With peak pressures, the reliability was found to be excellent for most sites of the foot with the two-step technique. The heel and first metatarsal head produced poor results using the mid-gait technique. In most respects, as with all other variables measured, the reliability of the two-step method was found to be better than the mid-gait technique.

The findings with respect to reliability of measurements between the two data collection methods may be related to greater variability of walking speed of test subjects associated with the mid-gait technique. In view of the technique of the two-step method, which permits only two steps before contacting the platform, it is possible that each subject's contact speed is reasonably consistent between trials. Whereas, with the mid-gait method, subjects select their own walking pace, which may vary slightly between trials, affecting recorded plantar measurement variables, as has been demonstrated by Rosenbaum et al. (1994).

Importantly, the results of the ANOVA indicate that for contact area, contact time (with the exception of the metatarsal heads), maximum force and peak pressure, there were no significant differences between the two data collection techniques. While fundamental plantar pressure loading data were collected and analysed, the derived measures of force-time and pressure-time-integrals were not assessed. Given that significant differences in contact time of the metatarsal heads was seen, it is likely that force and pressure impulse measurements recorded by the two data collection techniques, would also demonstrate some significant differences.

In summary, the reliability of most measurement variables at most sites of the foot was found to be good to excellent, with the two-step method yielding higher overall ICC values than the mid-gait method. No significant differences were found between most plantar loading measurements obtained from the two data collection techniques for most sites of the foot. The results suggest that the two-step technique may be used with confidence in place of the mid-gait method, where the clinician or researcher deems this technique to be preferable. However, it is recommended that the researcher or clinician adhere to either the mid-gait or the two-step method of data collection whenever a series of plantar loading measurements are taken for analysis.

3.4 LIMITATIONS

As only normal subjects were used in this study, it is possible the results may have been different for subjects with structural foot pathology such as hallux valgus or hallux limitus or other conditions affecting gait.

CHAPTER FOUR

NORMAL VALUES OF PLANTAR PRESSURE MEASUREMENTS USING THE EMED-SF SYSTEM*

Adapted from *Bryant, A., Tinley, P., and Singer. K. (1999). Normal values of plantar pressure measurements using the EMED-SF system. Journal of American Podiatric Medical Association. 90(6), 295-299.

4.0 RATIONALE OF THE STUDY

Plantar pressure measurement technology has the potential in podiatric medicine and surgery to provide the clinician with important information when assessing changes to foot function over time or the effects of therapeutic intervention (Alexander et al., 1990). The results obtained from plantar pressure measurement studies in clinical practice may be made more meaningful by comparing test values with normative values of potentially useful parameters such as peak pressure, mean pressure and pressure-time-integrals. The uses of the Novel Systems for plantar loading measurements in platform or in-shoe mode has previously been described (Graf, 1993). This paper outlines the normal values of plantar pressure measurements at ten sites of the foot of thirty normal subjects, using the two-step method of data collection outlined by Meyers-Rice et al. (1994) by employing an EMED SF system.

While the mid-gait data collection technique is an accepted protocol for plantar pressure measurement studies, the two-step technique employed may be more appropriate for use in clinical practice. From a practical point of view, the two-step method requires less floor space and is easier for most subjects. In addition, the time required to collect data from repeated trials of a given subject is less than with the mid-gait method. Furthermore, patients with insensate feet or significant medical problems may find it difficult to accomplish a prolonged data recording session using the mid-gait method, and indeed they may be placed at risk of injury (Myers-Rice et al., 1994). Similarly, subjects with gait or visual disturbances, or those with poor co-ordination may have difficulty in making contact with the pressure platform in the required free-flowing manner which may effect the quality of data collected (Cavanagh et al., 1992).

Since many factors may influence plantar pressure measurements, such as the equipment used (Hughes et al., 1993), cadence, step length and walking speed (Rosenbaum et al., 1994), the consistency of measurement technique is most important (Cavanagh et al., 1992; Hughes et al., 1991; Lord et al., 1986). Similarly, the reliability and repeatability of any testing equipment used must be of an acceptable standard. The overall accuracy of the EMED-F system has been described as good with less than 5% measurement error being reported for pressure/force variables (Morlock, 1991).

Previous research has investigated normal values of certain pressure parameters, particularly, peak pressure, using the mid-gait recording technique and a variety of platform systems (Bennett & Duplock, 1993; Hughes et al., 1993; Kaliszer et al., 1989; Shorten et al., 1989). Normal values for mean pressure and pressure-time-integral have not been often cited in the literature. The purpose of the present study was to record normal reference range values of selected plantar pressure measurements, in ten regions of the foot from repeated trials of thirty normal subjects employing the two-step method of data collection, using the EMED SF force plate and computer equipment.

4.1 METHOD

4.1.1 Subjects

Thirty healthy volunteers (18 females and 12 males) with a mean age of 39.8yrs (23-68yrs), mean weight of 70.1kg (48.5-96.6kg) and mean height of 168.7cm (156-185cm) agreed to participate in the study. All subjects were screened by interview and physical examination for obvious foot or gait abnormalities and had no history of significant foot or lower limb pathology in the preceding 12 months. Subjects were excluded from the study if clinical signs of pes valgus or pes cavus or forefoot pathology such as hallux valgus or hallux limitus were noted. No attempt was made to differentiate between male and female subjects as previous studies have observed little differences in plantar pressure measurements between sexes (Bennett and Duplock, 1993; Shorten et al., 1989; Soames, 1985). Written consent was obtained from each subject with approval of the Human Research Ethics Committee of Curtin University of Technology.

4.1.2 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

4.1.3 Procedure

Each subject was familiarised with the testing procedure by walking over the platform at his or her own self-selected comfortable pace several times. The subject's starting position was determined such that the first step was with the opposite foot from that being tested, with the test foot making contact with the platform on the second step from the starting position. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Each subject had data collected from three trials of the left foot, which were used in the subsequent analyses.

4.1.4 Data and statistical reporting

The foot of each subject was divided into 10 regions or masks using the EMED Automask software®. Masks for the heel, mid-foot, first-fifth metatarsal heads, hallux, second toe and third-fifth toes were selected for analysis. Using the EMED Multimask® software, peak pressure [N/cm^2], mean pressure [N/cm^2] and pressure-time-integrals [(N/cm^2)s], for the various masks were then generated and transferred to a spreadsheet for descriptive statistical reporting.

4.2 RESULTS

Mean values of selected plantar pressure measurements recorded from three trials of the left foot of 30 normal subjects was obtained. The highest mean values of peak pressure, average pressure and pressure-time-integrals were found in the heel, second and third metatarsal heads and the hallux. The greatest standard deviation of measurement was noted in the mid-foot, fifth metatarsal head and lesser digits. The regions of the foot that demonstrated the smallest standard deviations from the mean value, for most variables, were the heel and the second and third metatarsal heads. The regions of the foot exhibiting the greatest variation of measurement of the pressure variables tested were the mid-foot, fifth metatarsal and the lesser toes. This finding is illustrated for peak pressure of the second and fifth metatarsal heads and demonstrates greater variation of between-trials measurements of the fifth metatarsal head. See Figure 4.1.

Mean peak pressure and mean average pressure values showed similar trends at all regions of the foot studied, with average pressures approximately 50% less than peak pressures. See Figure 4.2. Descriptive statistical data of mean peak pressure, average pressure and pressure-time-integral measurements for 10 regions of the feet of 30 normal subjects, using the two-step method of data collection are presented in Table 4.1.

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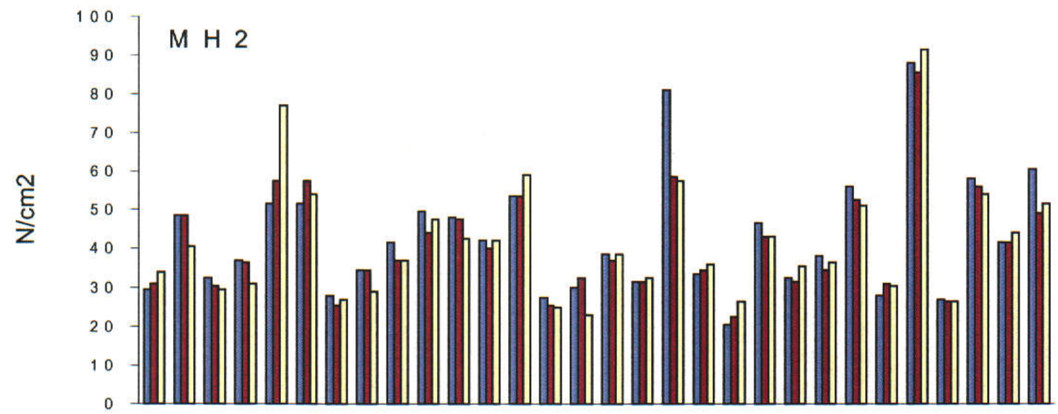
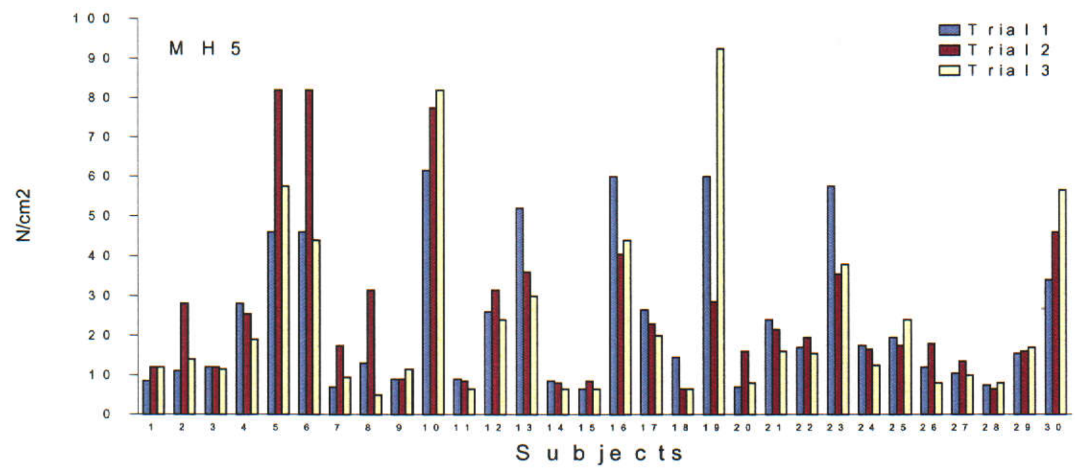
Table 4.1 Mean values of peak pressure, average pressure and pressure-time-integrals in the plantar regions of 30 normal subjects.

Region of foot	PP (N/cm^2)	Ave P (N/cm^2)	PTI (N/cm^2)s
Heel	35.0 [7.8]	16.7 [2.4]	8.0 [2.1]
Mid-foot	7.3 [3.1]	3.9 [2.5]	2.1 [1.2]
MH1	29.0 [11.6]	12.2 [3.3]	9.1 [3.5]
MH2	42.0 [14.7]	18.8 [4.1]	12.6 [4.0]
MH3	36.6 [11.4]	15.4 [3.2]	11.9 [3.8]
MH4	25.1 [10.3]	11.4 [3.9]	8.8 [3.8]
MH5	24.9 [20.7]	8.9 [4.3]	7.5 [5.5]
HX	44.2 [19.7]	13.9 [3.8]	11.0 [6.3]
2^{nd} toe	22.3 [9.3]	7.8 [2.5]	5.0 [2.6]
3rd-5^{th} toes	15.9 [7.8]	5.0 [1.8]	3.8 [2.0]

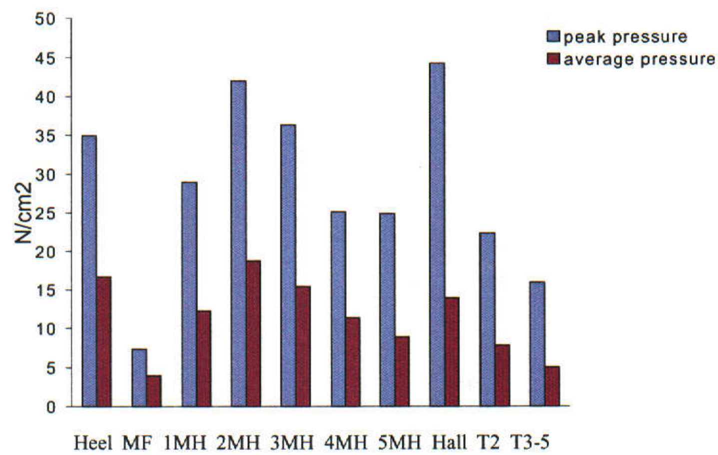
MH = metatarsal head, HX = hallux, [ ] = Standard deviation, Ave P = average pressure, PP = peak pressure, PTI = pressure-time-integral





MH2 = 2nd metatarsal head, MH5 = 5th metatarsal head

Figure 4.1 Comparison of between-trials variation of peak pressure beneath second and fifth metatarsal heads in three trials of 30 normal subjects.



MF = mid foot, MH = metatarsal head, T = toe

Figure 4.2 A comparison of peak pressure and average pressure measurements of 10 regions of the foot of 30 normal subjects.

4.3 DISCUSSION

With respect to mean peak pressure distribution, the highest values were found under the heel, second and third metatarsal heads and the hallux. These results are in agreement with Bennett and Duplock (1993), who used a Musgrave system, and Shorten et al. (1989) who used an EMED SF system. Both authors grouped the central forefoot, rather than obtaining pressure data for each metatarsal head, but did mask the heel region into medial and lateral sections. The highest peak pressures were also found under the hallux and second metatarsal heads by Hayafune et al. (1999), using an EMED-SF system investigating plantar pressure distribution in the forefoot of 42 healthy subjects. Similarly, Hughes et al. (1993), using an EMED F-System, also reported highest pressures in the region of the central forefoot and hallux. Peak pressures were seen to vary most under the fifth metatarsal head, mid-foot and third-fifth toes, with other regions exhibiting more consistent measurements. Some variations in pressure measurements will inevitably be found when different subjects, test conditions, methodologies and equipment are employed (Hughes et al., 1993).

Normal reference range values for mean average pressure followed similar trends as peak pressure. Average pressures were understandably lower and tended to show less variation for each region of the foot than peak pressures. The least variation of plantar measurements were found under the heel, second and third metatarsal heads, suggesting the heel and central forefoot region is functionally the most stable area of the foot during the stance phase of gait.

The greatest variation of values was found under the mid-foot and toes. Foot morphology may play a role in accounting for the large variation in peak pressure and maximum force seen in the mid-foot. This may be related to lateral arch height, for mid-foot contact essentially corresponds to the cuboid/fifth metatarsal region of the foot. Similarly, lesser digital function would seem to vary considerably, even between normal subjects, and may be responsible for the large variation of measurements seen in this area of the foot. While previous research suggests that there is some association between peak pressure measurements and foot structure (Cavanagh et al., 1997; Morag & Cavanagh, 1999) or foot type (Walker & Fan, 1998), the relationships between foot structure and function, as measured by plantar pressure measurement requires further investigation.

The measurement of pressure-time-integral has been proposed as a potentially valuable parameter in clinical practice (Soames, 1985) and is thought to be important in the pathogenesis of skin lesions (Fuller, 1996). Such measurements may prove to be useful in clinical practice, particularly in the management of the diabetic or insensate foot. Pressure-time-integral values were highest under the second and third metatarsal heads and hallux, and the greatest variation was noted under the fifth metatarsal head and toes.

In summary, mean peak pressure values recorded by the two-step method were in broad agreement with previously reported measurements collected by the mid-gait technique. Maximum values were found in the heel, second and third metatarsal heads and hallux, with the greatest variation of measurement noted in the mid-foot, fifth metatarsal head and lesser digits.

4.4 LIMITATIONS

The main limitation of the study was that data from only thirty subjects were used in the statistical analyses of the results. An expanded study using data from a larger sample of subjects may have produced different results. A second limitation of the study was that normative values of only peak pressure, mean pressure and pressure-time-integral were calculated and presented.

CHAPTER FIVE

A COMPARISON OF RADIOGRAPHIC MEASUREMENTS IN NORMAL, HALLUX VALGUS AND HALLUX LIMITUS FEET*

Adapted from *Bryant, A., Tinley, P., and Singer, K. (2000). A comparison of radiographic measurements in normal, hallux valgus and hallux limitus feet. The Journal of Foot and Ankle Surgery. 39(1), 39-43.

5.0 RATIONALE OF THE STUDY

Weight-bearing radiographs are thought to provide an accurate reflection of the structural (Cavanagh et al., 1997) and functional nature of the foot (Kaschak & Lane, 1988; Gamble & Yale, 1975), and are often used by podiatric and orthopaedic surgeons in the pre-operative assessment of first metatarso-phalangeal deformities (LaPorta et al., 1974; Smith et al., 1984). While many reports exist in the literature describing the radiographic differences between normal and hallux valgus feet, relatively little research has been conducted comparing radiographic measurements between normal and hallux limitus feet, or between hallux valgus and hallux limitus feet.

Various authors (Gamble & Yale, 1975; Osher, 1994; Gentili et al., 1996; Steel et al., 1980), have established normal values for most weight-bearing foot radiographic measurements used in this study and are summarised in Table 5.1.

While radiographic values of certain measures of weight-bearing dorso-plantar radiographs reported for hallux valgus deformity have been similarly established with good agreement (LaPorta et al., 1974; Osher, 1994; Hardy & Clapham, 1951; Weissman, 1983), radiographic measurements of lateral views are rarely cited in the literature. Assessment of hallux valgus, therefore, has traditionally emphasised measurements of the deformity in the transverse plane only (Weissman, 1983). Radiographic assessment of hallux limitus, on the other hand, commonly focuses on the stage of degenerative joint

Table 5.1 Accepted normal values of measurements of weight-bearing radiographs.

Author	Dorso-plantar view		Author	Lateral view	
Gentili et al (1996)	maa	≤15°	Osher (1994)	cia	18-23°
Gentili et al (1996)	mpa	8-12°	Osher (1994)	tda	19-25°
Osher (1994)	haa	5-15°	Osher (1994)	tca	42-48°
Osher (1994)	hipa	<10°	Gentili et al (1996)	1mda	19-25°
Gamble and Yale (1975)	mba	142°	Osher (1994)	5mda	11-19°
LaPorta et al (1974)	mpd	±2mm		nht	n/a
Steel et Al (1980)	mw	75-86mm			

Dorso-plantar view:
maa = metatarsus adductus angle
mpa = metatarsus primus adductus angle
haa = hallux abudctus angle
hipa = hallux interphalangeal angle
mba = metatarsal break angle
mpd = 1st metatarsal protrusion dist
mw = metatarsal width (mm)

Lateral view:
cia = calcaneal inclination angle
tda = talar declination angle
tca = talaocalcaneal angle
1mda = 1st metatarsal declination angle
5mda = 5th metatarsal declination angle
nht = navicular height (mm)

disease present in the first metatarsophalangeal joint, with little emphasis being placed on structural radiographic measurements in the transverse or sagittal planes (Camasta, 1996).

The reliability and repeatability of foot radiographs have been investigated with varying results. The inter- and intra-observer reliability of most radiographic measurements of the foot have been found to be reasonably good (Saltzman et al., 1994; Kilmartin et al., 1992), with intra-observer reliability reported to improve with experience (Brage et al., 1997). The consistency of radiographic measurements may be improved by employing a standardized radiographic technique which reduces magnification and distortion effects (Camasta et al., 1991; McCrea et al., 1977).

The purpose of the present study was to investigate the differences between weight-bearing radiographic foot measurements of 30 normal subjects compared with 30 hallux valgus and 30 hallux limitus subjects.

5.1 METHOD

This study was part of a larger research project investigating the effects of surgery on foot function of patients with hallux valgus and hallux limitus. As such, the research was approved by the Human Research and Ethics Committee of Curtin University of Technology, including the privilege of x-raying the feet of 30 control subjects. The nature and purpose of the research was explained, and written consent was obtained from all subjects.

5.1.1 Subjects

Control subjects were obtained from various sources, while subjects with hallux valgus or hallux limitus were recruited from the private practices of three local podiatrists. For the latter groups, pre-operative radiographs were supplied by the podiatrists and no additional radiographs were ordered. All patients were x-rayed in their relaxed stance position in a standardized fashion.

Control subjects were excluded from the study if they had clinical symptoms or radiological signs of either condition being investigated, had any obvious musculoskeletal abnormality of the lower limb, had undergone previous relevant foot surgery, or had suffered a significant injury to the lower limb in the previous twelve months. Hallux valgus and hallux limitus subjects all had signs and symptoms of first metatarsophalangeal joint deformity of sufficient severity for them to seek corrective surgery. Subjects were excluded from the study if they had a history of previous related foot surgery, inflammatory joint disease or other syndromes, which could predispose to either condition. Subject demographics are presented in Table 5.2.

Table 5.2 Demographics of subjects undergoing radiographic examination.

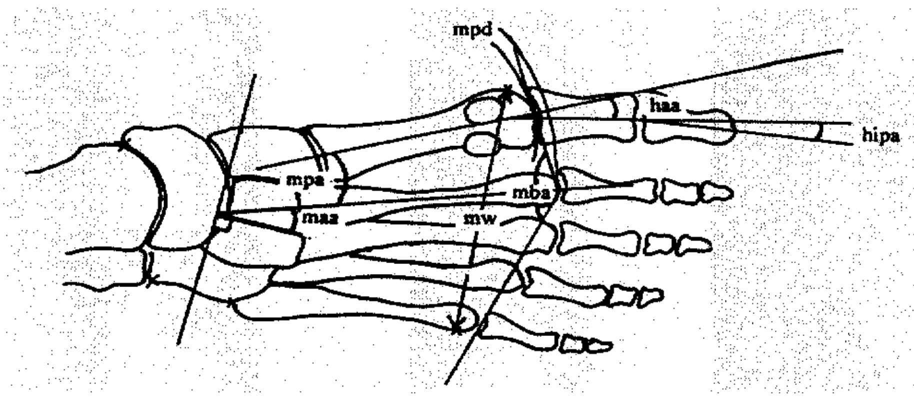
Subjects	n	gender	mean age [yrs]	BMI
Normals	30	12m/18f	39.8 (23-68)	24.6 [3.8]
Hallux valgus	30	3m/27f	51.3 (28-74)	22.6 [4.7]
Hallux limitus	30	9m/21f	52.8 (28-67)	26.1 [4.4]

m = male, f = female, ( ) = range, [ ] = standard deviation, BMI = body mass index

5.1.2 Radiographic measurement reliability

To assess the reliability of radiographic measurements used in the study, an intra-observer measurement reliability study was conducted. Various angular and linear measurements were made from six dorso-plantar and six lateral weight-bearing foot radiographs on three separate occasions. After each measurement session, the radiographs were wiped clean of any pencil marks and re-measured at random.

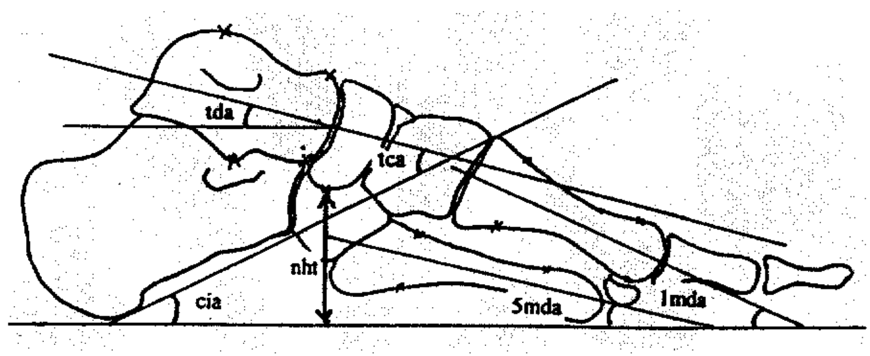
The various angular and linear measures taken from dorso-plantar and lateral radiographs, which were recorded, tested for intra-rater reliability of measurement, and used in the analyses are depicted in Figure 5.1.



Dorso-plantar view:

maa = metatarsus adductus angle
mpa = metatarsus primus adductus angle
haa = hallux abudctus angle
mw = metatarsal width (mm)
hipa = hallux interphalangeal angle
mba = metatarsal break angle
mpd = 1st metatarsal protrusion distance (mm)

Figure 5.1 Angular and linear measurements of dorso-plantar foot radiographs



Lateral view:

cia = calcaneal inclination angle
tda = talar declination angle
tca = talocalcaneal angle
1mda = 1st metatarsal declination angle
5mda = 5th metatarsal declination angle
nht = navicular height (mm)

Figure 5.2 Angular measurements of lateral foot radiographs

5.2 RESULTS

Intraclass correlation coefficients (ICC's) were calculated for all radiographic measurements tested and those with ICC's of 0.75 or greater, indicating acceptable reliability (Portney & Watkins, 1993), were employed in the study. See Table 5.3 for details.

With respect to dorso-plantar measurements, one way analysis of variance demonstrated significantly higher hallux abductus and metatarsus primus adductus angles in the hallux valgus group compared with both controls and hallux limitus groups. Similarly, significantly higher values of hallux interphalangeal angle were found for the hallux limitus group when compared with the hallux valgus group. Measurements of the first metatarsal protrusion distance and metatarsal width were also significantly greater in the hallux valgus group when compared with the control and hallux limitus groups. Lateral radiographic measurements demonstrated no significant differences between any of the groups tested.

Measurement data were generated and transferred to a spreadsheet for descriptive statistical reporting and analysis using SPSS-X. To assess significant differences between groups, a one way analysis of variance was conducted with the significance level at $p<0.05$. Table 5.4 summarizes the descriptive data and results of the statistical analysis.

Table 5.3 Intra-rater reliability of radiographic measurements.

	Dorso-plantar view			Lateral view	
maa	F-value	1.25	cia	F-value	0.15
	p-value	0.33		p-value	0.86
	ICC(3,1)	0.92		ICC(3,1)	0.87
mpa	F-value	0.06	tda	F-value	0.31
	p-value	0.94		p-value	0.74
	ICC(3,1)	0.91		ICC(3,1)	0.85
haa	F-value	1.13	tca	F-value	0.62
	p-value	0.36		p-value	0.56
	ICC(3,1)	0.96		ICC(3,1)	0.86
hipa	F-value	0.01	1mda	F-value	0.34
	p-value	0.99		p-value	0.72
	ICC(3,1)	0.88		ICC(3,1)	0.87
mpd	F-value	1.00	5mda	F-value	0.15
	p-value	0.40		p-value	0.86
	ICC(3,1)	0.92		ICC(3,1)	0.77
mw	F-value	0.29	nht	F-value	1.0
	p-value	0.75		p-value	0.40
	ICC(3,1)	0.99		ICC(3,1)	0.92
mba	F-value	0.13			
	p-value	0.87			
	ICC(3,1)	0.92			

Dorso-plantar view:
maa = metatarsus adductus angle
mpa = metatarsus primus adductus angle
haa = hallux abductus angle
hipa = hallux interphalangeal angle
mpd = 1st metatarsal protrusion dist (mm)
mw = metatarsal width (mm)
mba = metatarsal break angle

Lateral view:
cia = calcaneal inclination angle
tda = talar declination angle
tca = talaocalcaneal angle
1mda = 1st metatarsal declination angle
5mda = 5th metatarsal declination angle
nht = navicular height (mm)

Table 5.4 Mean measurements of radiographic parameters and significant differences between groups.

Radiographic measure	Controls	H valgus	H limitus	Sigificance
maa	17.7 [4.6]	19.7 [5.4]	18.2 [5.8]	0.312
mpa	9.4 [1.9]	13.0 [3.0]	8.6 [2.1]	<0.001*
haa	10.3 [4.0]	26.3 [6.3]	11.1 [3.7]	<0.001*
hipa	9.0 [3.3]	4.7 [3.8]	14.8 [20.6]	0.008*
mba	141.0 [6.9]	144.4 [7.6]	143.0 [7.3]	0.214
mpd	-1.1 [2.7]	2.0 [3.4]	0.3 [2.8]	0.001*
mw	89.1 [5.6]	93.4 [11.3]	88.0 [6.6]	0.029*
cia	24.2 [5.8]	24.4 [5.0]	24.8 [4.2]	0.877
tda	22.2 [3.7]	22.0 [4.5]	21.4 [4.4]	0.722
tca	46.2 [7.0]	46.7 [4.4]	46.1 [5.9]	0.915
1mda	20.4 [3.4]	21.7 [3.9]	22.0 [2.8]	0.143
5mda	10.1 [3.2]	10.6 [3.2]	13.2 [5.2]	0.060
nht	31.3 [7.3]	32.2 [8.2]	31.2 [6.9]	0.841

Dorso-plantar view:
maa = metatarsus adductus angle
mpa = metatarsus primus adductus angle
haa = hallux abudctus angle
hipa = hallux interphalangeal angle
mba = metatarsal break angle
mpd = 1st metatarsal protrusion dist
mw = metatarsal width [mm]
* significant (p<0.05)

Lateral view:
cia = calcaneal inclination angle
tda = talar declination angle
tca = talaocalcaneal angle
1mda = 1st metatarsal declination angle
5mda = 5th metatarsal declination angle
nht = navicular height [mm]
[ ] = standard deviation

In summary, a number of significant differences of radiographic measurements were found between control, hallux limitus and hallux valgus feet in the dorso-plantar views only. Significantly higher hallux interphalangeal angles were found in hallux limitus feet than with control or hallux valgus feet. Similarly, hallux valgus feet demonstrated significantly higher metatarsus primus adductus angles, metatarsal width, and first metatarsal protrusion distance compared with control and hallux limitus feet. Therefore, the hypothesis that radiographic measurements are different between normal, hallux limitus and hallux valgus feet is accepted.

5.3 DISCUSSION

Intra-rater reliability was found to be acceptable for seven dorso-plantar and six lateral radiographic measurements, suggesting that such measurements may be used with confidence by experienced individual clinicians, to assess and compare weight-bearing foot radiographs.

Radiographic values for control subjects were found to be in broad agreement with previously published normal reference range values (refer to Tables 5.1 and 5.4). Only metatarsal width was found to exceed the accepted normal values, and then only by 4%.

With respect to dorso-plantar radiographic measurements, no significant differences were found between metatarsus adductus and hallux valgus or hallux limitus. The association between metatarsus adductus and the development of hallux valgus has often been discussed in the literature, without consensus of opinion. While a number of authors believe there is a relationship between metatarsus adductus and hallux valgus (Root et al., 1977; La Reaux & Lee, 1987; Griffiths & Palladino, 1992), this relationship has been disputed by Kilmartin et al. (1991). Similarly, no significant differences were identified between metatarsal break angle and either hallux valgus or hallux limitus.

Metatarsus primus adductus was found to be significantly associated with hallux valgus compared to the control and hallux limitus groups and is in keeping with reports of various authors (Hardy & Clapham, 1951; Gottschalk et al., 1981; Saragas & Becker, 1995).

Hallux abductus is an obvious feature of hallux valgus deformity and it is not surprising to find a significant relationship between hallux adductus and hallux valgus.

Interestingly, this is not the case with hallux limitus, suggesting that most subjects with hallux limitus have a normally aligned hallucal proximal phallanx.

This study identified a significant association between hallux interphalangeal angle and hallux limitus when compared with hallux valgus. This finding is in keeping with that of Duke et al. (1982), who found an inverse relationship to exist between hallux abductus and hallux interphalangeus. The clinical importance of this finding is to suggest that patients with high hallux interphalangeal angles are less likely to develop hallux valgus but may be predisposed to the development of hallux limitus.

A positive metatarsal protrusion distance was found to be significantly associated with the presence of hallux valgus when compared with the control group. This finding is consistent with previous reports (Hardy & Clapham, 1951; Duke et al., 1982b), and suggests that a relatively long first metatarsal may be an aetiological factor in hallux valgus, and possibly precursory to the development of metatarsus primus adductus. From a surgical perspective, this finding suggests that intentional shortening of the first metatarsal, in concert with reduction of the intermetatarsal angle, may reduce the likelihood of the deformity returning in cases amenable to osteotomy. The literature however, is divided, with Saragas and Becker (1995) finding no such relationship and Villadot (1973) reporting short first metatarsals to be associated with hallux valgus and long first metatarsals to be associated with hallux limitus.

The relationship between metatarsal width and hallux valgus was found to be significant when compared with the control and hallux limitus groups. Metatarsal width, as a radiographic measure, is infrequently mentioned in the literature, however it was found to be significantly correlated with hallux valgus in a goniometric study by Lamur et al. (1996). Clinically, this finding suggests that a broad forefoot is associated with the presence of hallux valgus, which may simply be related to increased metatarsus primus adductus, but intrinsically is worthy of further investigation.

With respect to all lateral radiographic measurements recorded, no significant relationship was found with any group. In particular, no significant relationship was identified between first metatarsal declination angle (synonymous with metatarsus primus elevatus) and hallux limitus, as has been reported by various authors (Camasta, 1996; Youngswick, 1982). The finding is however, consistent with that of Meyer et al. (1987), who also found no differences in first metatarsal elevation between normal, hallux valgus and hallux limitus feet.

Interestingly, no significant difference was found between first metatarsal protrusion distance and the presence of hallux limitus, as suggested by others (Villadot, 1973; Feldman et al., 1983), nor with first metatarsal declination angle. These findings suggest that excessive length and elevation of the first metatarsal were not aetiological factors in the development of hallux limitus in the subjects studied.

In summary, this study investigated the differences in weight-bearing, foot radiographs among normal subjects, those with hallux valgus and those with hallux limitus. An intra-rater reliability study of various x-ray measurements was conducted, utilizing seven dorso-plantar and six lateral measurements. The results showed that metatarsus primus adductus, increased metatarsal width, and a positive first metatarsal protrusion distance were associated with hallux valgus. Whereas, increased hallux interphalangeal angle was associated with hallux limitus.

5.4 LIMITATIONS

The main limitation of this study was that although the radiographic technique used was standardised, the same radiographer using the same radiographic equipment did not take all of the radiographs. A second limitation of the study is that data from only thirty subjects in each group were used in the statistical analyses and formulation of the results. Subjects in the hallux valgus and hallux limitus groups showed a bias towards female gender and increased age when compared with the control group, which may have influenced the results.

CHAPTER SIX

PLANTAR PRESSURE DISTRIBUTION IN NORMAL, HALLUX VALGUS AND HALLUX LIMITUS FEET*

Adapted from *Bryant, A., Tinley, P., and Singer, K. (1999). Plantar pressure in normal, hallux valgus and hallux limitus feet. The Foot. 9(3), 115-119.

6.0 RATIONALE OF THE STUDY

Modern plantar pressure measurement technology offers the clinician a potential means of investigating changes to foot function over time or the effects of therapeutic intervention (Alexander et al. 1990). The use of plantar pressure measurement is developing as the application of this technology evolves from the research laboratory into clinical practice (Cavanagh et al. 1996). While hallux valgus and hallux limitus are relatively common conditions often encountered in clinical podiatry (Landers, 1992; Banks & McGlamry, 1992), the relationship between plantar pressure distribution and these abnormalities has not been adequately researched. Indeed, comparisons of plantar pressure measurements between feet with hallux valgus and hallux limitus have not been previously published. The purpose of this study was to investigate the relationship between plantar pressure measurements in normal subjects and those with hallux valgus and hallux limitus.

Plantar pressure measurement technology has been applied to the study of hallux valgus with somewhat inconsistent results and studies on hallux limitus have received only scant reports in the literature. The reports in the literature, for both hallux valgus and hallux limitus, demonstrate considerable variation in methodology, including pressure recording equipment used, data collection techniques and selection of subjects. Not surprisingly, the results are quite inconsistent and suggest the need for further research in this area.

This study compared selected plantar pressure measurements in 30 normal subjects with 30 subjects with hallux valgus and 30 subjects with hallux limitus, using an EMED-SF system.

6.1 METHOD

This study was part of a larger research project investigating the effects of surgery on foot function in patients with hallux valgus and hallux limitus. As such, the research was approved by the Human Research Ethics Committee of Curtin University of Technology. The nature and purpose of the research was explained, and written consent was obtained from all subjects.

6.1.1 Subjects

Control subjects were volunteers obtained from various sources. Subjects with hallux valgus or hallux limitus were recruited from the private practices of local podiatrists. Control subjects were excluded from the study if they had clinical symptoms or radiological signs of either condition being investigated, had any obvious musculoskeletal abnormality of the lower limb, had undergone previous related foot surgery, or suffered a significant injury to the lower limb in the preceding 12 months. Hallux valgus and hallux limitus subjects all had signs and symptoms of first metatarsophalangeal joint deformity of sufficient severity for them to seek corrective foot surgery.

Hallux valgus was defined both radiographically and clinically, when the hallux abductus angle was 15° or greater, as measured from a dorso-plantar weight-bearing x-ray, and the subject was without pain or obvious limitation of passive first metatarsophalangeal joint motion. Hallux limitus was defined as painful limitation of passive first metatarsophalangeal joint motion, without concomitant radiographic evidence of hallux valgus. Subjects were excluded from the study if they had a history of previous related foot surgery or inflammatory joint disease. Subject demographics are listed in Table 5.2.

6.1.2 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

6.1.3 Procedure

Each subject was allowed familiarisation with the testing procedure by walking over the platform at their own self-selected comfortable pace several times. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Each subject had data collected from the left foot with the two-step method as outlined by Myers-Rice et al. (1994).

Each subject's starting position was determined such that the subject commenced walking with the opposite foot to that being tested, with the test foot making contact with the platform on the second step from the starting position. Five to seven trials of each foot were then collected for each subject, and after discarding any aberrant footprints, three were selected for further analysis.

6.1.4 Data and statistical analysis

The foot of each subject was divided into 10 regions or masks using the EMED Automask® software, and included the heel, mid foot, first-fifth metatarsal heads, hallux, second toe and third-fifth toe. Measurements of peak pressure [N/cm^2], mean pressure [N/cm^2], and pressure-time-integrals [$(N/cm^2)s$], for the various masks were then generated and transferred to a spreadsheet for statistical analysis using SPSS-X (Norusis, 1983).

Selected plantar pressure measurements of 10 regions of the foot of 30 normal, 30 hallux valgus and 30 hallux limitus subjects were recorded and one way analysis of variance employed to assess for significant differences between the groups, with the probability level at $p<0.05$.

6.2 RESULTS

Peak pressure measurements were found to be significantly different for hallux valgus feet with greater pressures beneath the first, second and third metatarsal heads, compared with both normal and hallux limitus feet ($p<0.001$). For feet with hallux limitus, only the third-fifth toe region recorded significantly increased pressures compared with the control group ($p<0.01$). See Table 6.1.

Mean average pressure values were significantly higher for hallux valgus feet beneath the second metatarsal head when compared with normal and hallux limitus feet ($p<0.005$), while both hallux valgus and hallux limitus groups showed higher peak pressures beneath the third metatarsal head when compared with normal feet ($p<0.005$). Similarly, hallux limitus feet recorded significantly higher pressures beneath the hallux ($p<0.05$) and the second toe when compared with normal and hallux valgus, and the third-fifth toes compared with normal feet ($p<0.005$).

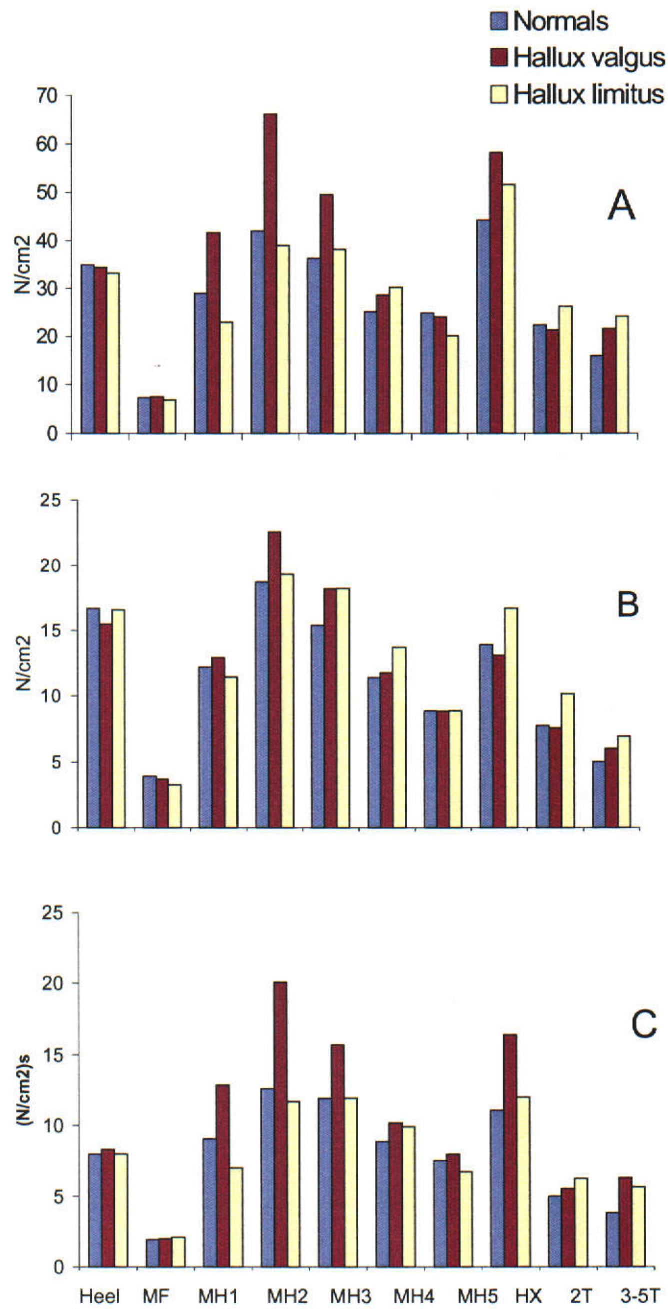
Pressure-time-integral (PTI) measurements, as would be expected largely mirrored the peak pressure results, with significantly higher recordings for hallux valgus feet beneath the first, second and third metatarsal heads when compared with normal and hallux limitus feet ($p<0.001$). Measurements for the hallux ($p<0.05$) and third-fifth toes ($p<0.01$) were also significantly higher in hallux valgus feet when compared with normal feet.

A comparison of mean values of peak pressure, mean pressure and pressure-time-integrals for normal, hallux valgus and hallux limitus feet is shown in Figure 6.1, indicating significant differences between hallux valgus and hallux limitus feet.

Table 6.1 Mean peak pressure measurements of thirty normal, hallux valgus and hallux limitus subjects with significant differences between groups.

	Mean peak pressure (N/cm^2)			
Mask	Controls	H valgus	H limitus	*P*
Heel	34.96	34.38	33.23	n/s
Mid-foot	7.32	7.54	6.87	n/s
1MH	28.96	41.64	22.98	<0.001*
2MH	41.95	66.11	38.98	<0.001*
3MH	36.28	49.51	38.21	<0.001*
4MH	25.11	28.62	30.26	n/s
5MH	24.86	24.07	20.09	n/s
Hallux	44.22	58.18	51.53	n/s
2^{nd} toe	22.32	21.30	26.26	n/s
3^{rd}-5^{th} toes	15.91	21.53	24.12	0.008*

n/s = not significant, *significant $p<0.05$, MH = metatarsal head



Significant differences between hallux valgus and hallux limitus ($p<0.05$), MF = mid foot, MH = metatarsal head, HX = hallux, 2T = 2nd toe, 3-5T = 3rd-5th toes

Figure 6.1 Mean peak pressure (A), average pressure (B), and pressure-time-integral (C) measurements of 30 normal, hallux valgus and hallux limitus subjects for each plantar region.

In summary, the results demonstrated a significant medial locus of mean peak pressure, mean average pressure and pressure-time-integral measurements beneath the second and third metatarsal heads in hallux valgus feet when compared with normal and hallux limitus feet. On the other hand, hallux limitus feet showed significantly higher measurements of mean average pressure and pressure-time-integral beneath the hallux and third to fifth toe regions when compared with normal and hallux valgus feet. Therefore, the hypothesis that plantar pressure measurements are different between normal, hallux valgus and hallux limitus feet is accepted.

6.3 DISCUSSION

In relation to subject demographics, although there is a degree of gender imbalance between the groups, this should not have adversely affected the results as plantar pressure measurements have been shown to vary little between men and women (Somes et al., 1982; Shorten et al., 1989; Bennett & Duplock, 1993).

With respect to the hallux valgus group, the distribution of mean peak pressures on the plantar aspect of the foot demonstrated significantly higher medial forefoot pressures compared with both normal and hallux limitus feet, with increased pressure beneath the second, third and first metatarsal heads respectively. Mean average pressures also showed similar significant locus of pressure to the second and third metatarsal heads, when compared with normal subjects. These findings are in keeping with Plank (1995), and supports the concept of foot pronation being an important aetiological factor in the development of hallux valgus, as proposed by various authors (Root et al., 1977; Gerbert & Sokoloff, 1981; Landers, 1992) and supported by the research of Stephenson (1990).

Subjects with hallux limitus on the other hand, demonstrated increased peak pressure in the third-fifth toe region when compared with normal feet. Mean average pressures were significantly elevated under the third metatarsal head, hallux and all lesser toes, when compared with normal subjects. These findings may be explained in terms of the pathomechanics of the first metatarsophalangeal joint, inherent in the deformity of hallux limitus. A reduced capacity for the first metatarsal to adequately plantar flex during the propulsive phase of gait, leads to a restricted first metatarsophalangeal joint range of motion and decreased mobility of the sesamoid apparatus. This eventuates in forceful approximation of the proximal phalangeal base into the head of the first metatarsal (Banks & McGlamry, 1992; Camasta, 1996; Durrant & Siepert, 1993), resulting in increased mean pressure of the hallux with forefoot load being transferred laterally beneath the third metatarsal heads and lesser toes.

Pressure-time-integrals are thought to be important in the pathogenesis of skin lesions, and are therefore potentially valuable measurement parameters in clinical practice (Fuller, 1996). Hallux valgus feet demonstrated a significant increase in pressure-time-integrals beneath the first, second, third metatarsal heads and hallux compared with normal and hallux limitus feet. This finding is consistent with clinical experience, which indicates that patients with long-standing hallux valgus are prone to develop hyperkeratotic lesions on the sole of the foot at these sites.

In summary, of the 30 normal, 30 hallux valgus and 30 hallux limitus subjects studied, hallux valgus feet demonstrated significantly higher medial forefoot measurements of peak pressure, average pressure and pressure-time-integral under the first, second and third metatarsal heads. While hallux limitus feet showed significantly higher peak pressure, average pressure and pressure-time-integral measurements under the hallux and lesser toes, indicating a more lateral forefoot distribution of load.

6.4 LIMITATIONS

The main limitation of this study was that although the radiographic technique used was standardised, the same radiographer using the same radiographic equipment did not take all of the radiographs. A second limitation of the study is that data from only thirty subjects in each group were used in the statistical analyses and formulation of the results. Subjects in the hallux valgus and hallux limitus groups showed a female gender and increased age bias compared with the control group, which may have influenced the results. A third limitation was that only peak pressure, average pressure and pressure-time-integral were examined and that other plantar pressure measurement parameters were not tested.

CHAPTER SEVEN

RADIOGRAPHIC MEASUREMENTS AND PLANTAR PRESSURE DISTRIBUTION IN NORMAL, HALLUX VALGUS AND HALLUX LIMITUS FEET*

Adapted from *Bryant, A., Tinley, P., and Singer, K. (2000). Radiographic measurements and plantar pressure distribution in normal, hallux valgus and hallux limitus feet. The Foot. 10(1), 18-22.

7.0 Rationale Of The Study

The conventional view that form follows function is a scientific dictum accepted by most anatomists and clinicians alike. The investigation of foot structure and function may take many forms, including the use of static weight-bearing x-rays and plantar pressure measurements. Radiographs are thought to provide an accurate reflection of the structural (Cavanagh et al., 1997) and functional nature of the foot (Gamble & Yale, 1975; Kaschak & Lane, 1988), and are often used by podiatric and orthopaedic surgeons in the pre-operative assessment of first metatarsophalangeal deformities (LaPorta et al., 1974; Smith et al., 1984). Modern plantar pressure measurement technology on the other hand, offers the clinician a potential means of investigating changes to foot function over time (Alexander et al., 1990). However few reports in the literature exist concerning the relationship between foot structure, as determined by radiographic measurements, and plantar pressure distribution (Cavanagh et al., 1997). The purpose of this study was to investigate the relationship between osseous foot structure and selected plantar pressure measurements in normal subjects and those with hallux valgus and hallux limitus.

While previous research has investigated the relationship between structural and functional factors and plantar pressure distribution, only the heel, mid-foot, first metatarsal head were considered in normal subjects (Cavanagh et al., 1997; Morag & Cavanagh, 1999). Cavanagh et al. (1997) examined 50 normal subjects and used an EMED-SF system to obtain pressure measurements, finding that only 38% and 31% of the variance in peak pressure under the heel and first metatarsal head respectively, could be related to radiographic findings. The predictors of increased pressure included soft tissue thickness beneath the sesamoids and calcaneous, and first metatarsal inclination and calcaneal inclination angles.

Using a similar number of asymptomatic subjects and an EMED-SF2 force platform, Morag and Cavanagh (1999) proposed a regression model to explain peak pressure distribution, involving subject age, certain radiographic measurements, joint range of motion and muscle activity. They found radiographic factors to be most important, concluding that a short second metatarsal and reduced plantar skin thickness beneath the sesamoids appeared to be related to increased pressure beneath the first metatarsal head. Similarly, reduced soft tissue mass beneath the heel was thought to be associated with increased peak pressure at this location of the foot.

This study investigated the relationship between static osseous radiographic foot measurements and mean peak pressure recordings of 10 selected regions of the foot in 30 normal, hallux valgus and hallux limitus subjects.

7.1 METHOD

The study was part of a larger research project investigating the effects of surgery on foot function in patients with hallux valgus and hallux limitus. As such, the research was approved by the Human Research Ethics Committee of Curtin University of Technology, including the permission to x-ray the feet of 30 control subjects. The nature and purpose of the research was explained and written consent obtained from each subject.

7.1.1 Subjects

Control subjects were obtained from various sources, while hallux valgus/limitus were recruited from the private practices of local podiatrists. For these groups, pre-operative radiographs were supplied by the podiatrists and no additional radiographs were required. Control subjects were excluded from the study if they had: clinical symptoms or radiological signs of either condition being investigated; had any obvious musculoskeletal abnormality of the lower limb; had undergone previous relevant foot surgery; or suffered a significant injury that may have effected their gait in the previous twelve months. Hallux valgus/limitus subjects all had signs and symptoms of first metatarsophalangeal joint deformity of sufficient severity for them to seek corrective surgery. Hallux valgus subjects all had relatively normal range of motion of the first metatarsophalangeal joint, with hallux abductus angles of 20° or more. Hallux limitus subjects all demonstrated painful restriction of first metatarsophalangeal joint motion (< 65°) and no clinical or radiographic signs of concurrent hallux valgus. Subjects were excluded from the study if they had a history of previous related foot surgery or inflammatory joint disease. Subject demographics are listed in Table 5.1.

7.1.2 Radiographic measurement reliability

Various angular and linear measures were made from weight-bearing dorso-plantar and lateral foot radiographs, which were recorded, tested for intra-rater reliability of measurement, and used in the analyses. Refer to Figure 5.1.

To assess the reliability of radiographic measurements used in the study, a number of angular and linear measurements were made from six dorso-plantar and six lateral weight-bearing foot radiographs on three separate occasions. After each measurement session, the radiographs were wiped clean of any pencil marks and re-measured at random.

Intraclass correlation coefficients (ICC's) were generated and those measurements with ICC's of 0.75 or greater, indicating acceptable reliability, were employed in the study (Portney & Watkins, 1993). See Table 7.1 for details.

Table 7.1 Intra-rater reliability ICC values of static weight-bearing dorso-plantar and lateral radiographic measurements.

Dorso-plantar view	ICC	Lateral view	ICC
Metatarsus adductus angle	0.92	Calcaneal inclination angle	0.87
Metatarsus primus adductus angle	0.91	Talar declination angle	0.85
Hallux abudctus angle	0.96	Talocalcaneal angle	0.86
Hallux interphalangeal angle	0.88	First metatarsal declination angle	0.87
Metatarsal protrusion distance	0.92	Fifth metatarsal declination angle	0.77
Metatarsal width	0.99	Navicular height	0.92
Metatarsal break angle	0.92		

ICC = intraclass correlation coefficient

7.1.3 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

7.1.4 Procedure

Each subject was allowed familiarisation with the testing procedure by walking over the platform several times. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Each subject had data collected from the left foot with the two-step method as outlined by Myers-Rice et al. (1994). This recording technique has been demonstrated to provide similar and at least as reliable pressure measurements as the more traditional mid-gait method (Bryant et al., 1999b).

Each subject's starting position was determined such that the subject commenced walking with the opposite foot to that being tested, with the test foot making contact with the platform on the second step from the starting position. Several trials of each foot was then collected for each subject, and after discarding any aberrant footfalls, three were selected for further analysis.

7.1.5 Data and statistical analysis

The foot of each subject was divided into 10 regions or masks using the EMED Automask software. Masks for the heel, mid foot, first-fifth metatarsal heads, hallux, second toe and third – fifth toes were selected for analysis. Peak pressure (N/cm^2) for the various masks were then generated and transferred to a spreadsheet for statistical analysis using SPSS-X.

To test for the presence of a linear relationship between mean peak pressure recordings and radiographic measurements, Pearson product-moment correlation coefficients were generated for normal, hallux valgus and hallux limitus groups.

7.2 RESULTS

Of the various linear and angular radiographic measures tested for intra-rater reliability, seven dorso-plantar and six lateral parameters achieved acceptable intraclass correlation coefficients of 0.75 or greater. Refer to Table 7.1.

A comparison of the dynamic peak pressures at 10 sites of the plantar aspect of 30 normal, hallux valgus and hallux limitus feet demonstrated no correlation between any radiographic measure and mean peak pressure recording at any region of the foot in either group of subjects. See Table 7.2 for details of radiographic versus plantar pressure measurements.

Table 7.2 Mean peak pressure and radiographic measurements of 30 normal, hallux valgus and hallux limitus feet.

	Normal	Hallux valgus	Hallux limitus
Peak pressure (N/m^2)			
heel	35.0 [7.6]	34.4 [12.4]	33.2 [10.4]
mid-foot	7.3 [3.2]	7.5 [3.5]	6.9 [3.2]
MH1	29.0 [11.3]	41.6 [25.4]	23.0 [8.7]
MH2	42.0 [14.8]	66.1 [23.9]	39.0 [11.5]
MH3	36.3 [11.5]	49.5 [14.9]	38.2 [9.7]
MH4	25.1 [10.3]	28.6 [13.3]	30.3 [10.5]
MH5	24.9 [20.8]	24.1 [22.1]	20.1 [10.3]
HX	44.2 [21.9]	58.2 [27.4]	51.5 [28.3]
T2	22.3 [9.1]	21.3 [17.3]	26.3 [12.4]
3-5T	15.9 [7.6]	21.5 [12.0]	24.1 [13.2]
Dorso-plantar radiographic measurements			
maa	17.7 [4.6]	19.7 [5.4]	18.2 [5.8]
mpa	9.4 [1.9]	13.0 [3.0]	8.6 [2.1]
haa	10.3 [4.0]	26.3 [6.3]	11.1 [3.7]
hipa	9.0 [3.3]	4.7 [3.8]	14.8[20.6]
mpd	-1.1 [2.7]	2.0 [3.4]	0.3 [2.8]
mw	89.1 [5.6]	93.4 [11.3]	88.0 [6.6]
mba	141.0 [6.9]	144.4 [7.6]	143.0 [7.3]
Lateral radiographic measurements			
cia	24.2 [5.8]	24.4 [5.0]	24.8 [4.2]
tda	22.2 [3.7]	22.0 [4.5]	21.4 [4.4]
tca	46.2 [7.0]	46.7 [4.4]	46.1 [5.9]
1mda	20.4 [3.4]	21.7 [3.9]	22.0 [2.8]
5mda	10.1 [3.2]	10.6 [3.2]	13.2 [5.2]
nht	31.3 [7.3]	32.2 [8.2]	31.2 [6.9]

MH = metatarsal head, HX = hallux
T2 = 2nd toe
maa = metatarsus adductus angle
mpa = metatarsus primus adductus angle
haa = hallux abudctus angle
hipa = hallux interphalangeal angle
mpd = metatarsal protrusion dist (mm)
mw = metatarsal width (mm)
mba = metatarsal break angle

[ ] = standard deviation
T3-5 = 3rd-5th toes
cia = calcaneal inclination angle
tda = talar declination angle
tca = talocalcaneal angle
1mda = 1st metatarsal declination angle
5mda = 5th metatarsal declination angle
nht = navicular height (mm)

The results demonstrate no significant correlation between dynamic peak pressure measurements in 10 regions of the foot with static weight-bearing radiographic measurements of 30 normal, hallux valgus and hallux limitus feet. Therefore the hypothesis that dynamic plantar pressure distribution in normal, hallux valgus and hallux limitus feet is related to static weight-bearing radiographic measurements of the foot is rejected.

7.3 DISCUSSION

The purpose of this study was to investigate the relationship between various static osseous radiographic foot measurements and dynamic mean peak pressure recordings of ten selected regions of the foot in 30 normal subjects and 30 subjects with hallux valgus and hallux limitus.

With respect to the various angular and linear radiographic parameters tested for intra-rater reliability, the results suggest that these measurements may be used with confidence, which is in keeping with findings of other researchers (Brage et al., 1997; Kilmartin et al., 1992; Saltzman et al., 1994). However a possible limitation of the study relates to the fact that foot radiographs were obtained from more than one radiology practice. While the general radiographic technique employed was standardised, the same radiographer, using the same equipment did not take every radiograph.

Previous research has identified various factors which seem to have some influence on peak pressure distribution within the foot. Such variables as walking speed (Rosenbaum et al., 1994) age (Kernozek & LaMott, 1995) and foot type (Walker & Fan, 1998), have been implicated as contributing to plantar pressure variation between subjects. Given the reliability of the two-step method of data collection, between-subject measurement error associated with variation of walking speed, would seem not to apply.

It would appear that only Cavanagh et al. (1997) and Morag and Cavanagh (1999) have reported on the relationship between plantar peak pressure measurements and static weight-bearing radiographic measurements of normal, asymptomatic feet. These studies concluded that only a proportion of the variance in dynamic plantar pressure was associated with radiographic measurements of foot structure, and that other factors, both regional and more proximal, contribute to pressure distribution within the foot.

This study found no direct relationship between osseous foot structure, as measured from static weight-bearing foot radiographs, and dynamic mean peak pressure measurements of ten regions of normal, hallux valgus and hallux limitus feet exists.

In summary, the results of this study suggest that dynamic peak pressure distribution beneath the sole of the foot is unrelated to the static weight-bearing radiographic parameters tested, in normal, asymptomatic subjects and those with hallux valgus or hallux limitus. Furthermore, that weight-bearing radiographic measurements tested may not be used to predict plantar peak pressure distribution. Other intrinsic or extrinsic biomechanical, physical and physiological factors, which may have an influence on plantar pressure distribution within the foot, require further investigation.

7.4 LIMITATIONS

The main limitation of this study was that although the radiographic technique used was standardised, the same radiographer using the same radiographic equipment did not take all of the radiographs. A second limitation of the study is that data from only thirty subjects in each group were used in the statistical analyses and formulation of the results. Subjects in the hallux valgus and hallux limitus groups showed a bias towards female gender and increased age when compared with the control group, which may have influenced the results. A third limitation of the study was that only peak pressure was correlated with radiographic measures and that other plantar pressure measurements were not tested.

CHAPTER EIGHT

PLANTAR PRESSURE MEASUREMENT AND RANGE OF MOTION CHANGES FOLLOWING HALLUX LIMITUS SURGERY

8.0 RATIONALE OF THE STUDY

Changes to plantar pressure measurements following surgical intervention on the first metatarso-phalangeal joint to address hallux limitus deformity has received scant attention in the literature. The 'Youngswick' osteotomy/cheilectomy is often performed to correct mild to moderate hallux limitus with the main objective to improve the range of motion of the first metatarsophalangeal joint and decrease the joint pain associated with the degree of arthrosis present. A review of the literature indicates that no reports have been published outlining pressure distribution changes within the foot or range of motion changes to the first metatarsophalangeal joint with respect to this operation.

8.1 METHOD

8.1.1 Subjects

Thirty-six healthy volunteers were recruited as control subjects and screened by interview to exclude any history of significant foot or lower limb pathology in the preceding twelve months and by physical examination for signs of any obvious foot or gait abnormalities. Control subjects were excluded from the study if clinical signs of pes valgus (pronated, flat foot) or pes cavus (supinated, high arched) or forefoot pathology such as hallux valgus or hallux limitus were noted. No attempt was made to differentiate between male and female subjects as previous studies have observed little differences in plantar pressure measurements between sexes. (Bennett & Duplock, 1993; Shorten et al., 1989; Soames, 1985) With approval of the Human Research Ethics Committee of Curtin University of Technology, written consent was obtained from each subject. Refer to Appendix C.

Seventeen subjects (23 feet) with hallux limitus were recruited from the private practices of local podiatrists. Hallux limitus subjects all had signs and symptoms of first metatarsophalangeal joint deformity of sufficient severity for them to seek advice on and subsequently undergo corrective foot surgery.

Hallux limitus was defined clinically as painful limitation of passive first metatarsophalangeal joint motion, and radiographically as grade I or II hallux limitus without concomitant evidence of hallux valgus. Subjects were excluded from the study if they had a history of previous related foot surgery or inflammatory joint disease. Each hallux limitus patient underwent a Youngswick procedure under general anaesthesia. Again, the author performed approximately 75% of the operations, along with the same group of surgeons as for the hallux valgus group. Each practitioner was well experienced with the procedure and used a standardised surgical technique. Refer to Appendix B. Subject demographics are listed in Table 8.1.

8.1.2 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

Data for each subject recording session were coded to ensure confidentiality of each subjects identity and available only to the author and the supervisors. All raw data are to be stored for seven years, as required by of the Human Research Ethics Committee of Curtin University of Technology. An IBM compatible computer was used to facilitate data organisation and analysis using appropriate software.

Table 8.1 Control and hallux limitus subject demographics

	Controls	Hallux limitus
n (subjects)	36	17
n (feet)	36	23
Gender	12m/24f	7m/10f
Mean age (yrs)	39.8 [12.0]	50.5 [8.6]
Range	23.0 - 68.0	36.0 - 66.0
Mean wt (kg)	70.1 [13.9]	74.4 [15.9]
Range	48.5 - 96.6	50.0 -101.0
Mean ht (cm)	168.7 [9.1]	168.1 [8.3]
Range	156.0-185.0	156.5-188.0
Mean BMI	24.6 [3.8]	26.1 [4.4]
Range	18.9 - 35.4	18.6 - 34.1

m = male, f = female, BMI = body mass index = $wt(kg)/ht(m)^2$,
[ ] = standard deviation

8.1.3 Procedure

8.1.3.1 Plantar pressure measurement data collection

Subjects were individually informed of the nature and intent of the proposed research and invited to participate. After written consent was obtained, each subject was allowed familiarisation with the testing procedure by walking over the platform at their own self-selected comfortable pace several times. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Each control subject had data collected from the left foot with the two-step method as outlined by Myers-Rice et al. (1994). Data were collected from the feet of subject's on whom surgical correction was to be performed and for the purposes of statistical analyses, each foot thereafter was treated as a single subject.

Each person's starting position was determined such that the individual commenced walking with the opposite foot to that being tested, with the test foot making contact with the platform on the second step from the starting position. Several trials of each foot were then collected for each person, and after discarding any aberrant footfalls, a minimum of three footprints were kept for further analysis. Plantar pressure measurement data of control subjects were collected at the beginning of the trial and subsequently repeated 24-months later. Data from hallux limitus subjects were collected pre-operatively and at three, six, 12, 18 and 24-months post-operation.

8.1.3.2 Range of motion of first metatarsophalangeal joint measurement

The intra-rater reliability of measurement of passive plantarflexion and dorsiflexion of the hallux at the first metatarsophalangeal joint with the foot in a relaxed non-weight bearing position was conducted using data from six control subjects. In a similar manner, passive dorsiflexion and plantarflexion of the hallux of each hallux limitus subject was measured pre-operatively and repeated at 24-months post-operation.

8.1.4 Data and statistical analysis

The foot of each subject was divided into 10 regions or masks using the Novel-ortho® software (version 08.7) 'Automask' program, to include the heel, mid-foot, first through fifth metatarsal heads, hallux, second toe and third to fifth toes. The Novel-win® software (version 08.7) 'Groupmask' program was then used to group together three recorded trials of each subject into a single data file. Each data file thus formed was subsequently analysed using the Novel-win® 'Groupmask Evaluation' program. Measurements of mean peak pressure [N/cm^2], pressure-time-integral [(N/cm^2)s], contact time [% roll-over-process], maximum force [% body weight] and force-time-integral [(% body weight)s], for the various masks were then generated and transferred to a Microsoft Excel 97 spreadsheet for statistical analysis using SPSS 10.0 for Windows.

During the collection period it became apparent that data from the heel, mid-foot and lesser digital masks exhibited very little variation between data collection times, while the forefoot seemed to present more dynamic changes, worthy of detailed statistical examination. Therefore, only masks within the forefoot, including the first to fifth metatarsal heads and the hallux were used in subsequent data analyses.

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8.2 RESULTS

With respect to control subjects, plantar pressure data were collected at zero and 24-months. The reliability of pressure/force measurements was examined by calculating intra-class correlation coefficients from data collected at zero months. Similarly, to examine for the correlation of pressure/force measurements with intra-subject factors, bivariate correlation matrices were generated using data collected at zero months. Changes to peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral measurements of control subjects between zero and 24-months were assessed by paired t-tests with alpha level at 0.05.

Changes to plantar pressure measurements of hallux limitus subjects were assessed over a 24-month period, with peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral measurements being assessed separately. Repeated measures multivariate analysis of variance and within-subject contrasts were used to identify significant pressure/force changes between zero to three months, three to six months, six to 12-months, 12 to 18-months, and 18 to 24-months. Univariate contrasts were used to identify significant overall changes between zero and 24-months. In addition, a comparison of significant differences between the various plantar pressure measurements of control and hallux limitus subjects at zero and 24-months were made using independent t-tests.

Finally, with regards to hallux limitus subjects, since the primary objective of the Youngswick procedure is to restore a normal range of sagittal plane motion of the hallux at the first metatarsophalangeal joint, a pre- and 24-month post-operation range of motion study on each subject was performed. Bivariate correlation matrices were subsequently used to assess for correlations between range of motion of the hallux and plantar pressure measurements.

8.2.1 Control data

8.2.1.1 Reliability of measurement of pressure/force variables of control subjects

To assess the intra-rater reliability of measurement for the various pressure data obtained from the hallux and 1^{st}-5^{th} metatarsal heads, intraclass correlation coefficients (ICC's) were calculated from three trials of 36-subjects using a two-way mixed effect model, absolute agreement definition, single measure ICC (Coakes and Steed, 1999). The results indicate generally good (>0.75) to excellent (>0.90) consistency of measurement as proposed by (Portney & Watkins, 1993), with the exception of contact time which produced relatively lower intraclass correlation coefficients. See Table 8.2.

8.2.1.2 Correlation of pressure/force variables with intra-subject factors of control group

To assess for the existence of a statistical relationship between subject variables such as age or body-mass-index with various plantar pressure/force variables, measured at the commencement of the experiment, bivariate correlation matrices were generated using Pearson's correlation coefficient with a significance level (2-tailed) of $p<0.05$. No significant correlation was found between either of these variables and any pressure variable tested, including peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral. See Appendix E.

To test for a statistical relationship between gender and plantar pressure/force variables of the forefoot as measured at the commencement of the experiment, an independent t-test was conducted. The Levene test for equality of variance was applied and demonstrated equal variances of each group for each pressure/force variable tested except for peak pressure and pressure-time-integral for the fourth metatarsal head. The results of the t-test show no significant differences for gender with any pressure/force variable in any region of the forefoot. The results are summarised in Appendix F.

Table 8.2 Intraclass correlation coefficients of plantar pressure measurements of three trials of 36 control subjects.

	PP	PTI	CT	MF	FTI
MH1	0.80*	0.88*	0.89*	0.84*	0.89*
MH2	0.97**	0.97**	0.73	0.92 **	0.93**
MH3	0.94**	0.96**	0.68	0.84*	0.89*
MH4	0.91**	0.94**	0.76*	0.83*	0.89*
MH5	0.91**	0.94**	0.71	0.82*	0.89*
HX	0.88*	0.91*	0.73	0.93**	0.91**

PP=peak pressure, PTI=pressure-time-integral, CT=contact time, MF=max force, FTI= force-time-integral, MH=metatarsal head, HX=hallux.* Good cor. (>0.75) ** Excellent cor. (>0.90)

8.2.1.3 Changes to plantar pressure measurements with time in control group

Plantar pressure measurements of peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral, for each control subject were recorded at the commencement of the experiment and 24-months later. The mean data of three trials of each subject for each recording session is presented in Appendix G.

To test for significant differences of pressure/force variables in control subjects between zero and 24-months, paired t-tests were conducted, with the significance level at $p<0.05$. Assumption testing for normality was conducted examining stem-and-leaf plots and boxplots, which demonstrated all pressure/force variables tested had normal distributions. The fourth and fifth metatarsal head areas were subject to small but significant decreases in all measurements except contact time. The first metatarsal head showed a small but significant decrease for maximum force and contact time, while the third metatarsal head showed a small but significant increase in pressure-time-integral over the 24-month period of observation. All other t-tests showed non-significant differences. See Table 8.3 for details.

Table 8.3 Descriptive statistics and paired t-test results of mean plantar pressure measurements of the forefoot of control subjects

	0 months	24-months	t	df	Sig (2-tailed)
Peak pressure (N/cm^2)					
MH1	28.57 [10.88]	30.25 [9.05]	-1.29	35	0.207
MH2	40.66 [15.57]	40.14 [14.46]	0.54	35	0.591
MH3	35.15 [11.27]	33.67 [11.31]	1.69	35	0.100
MH4	23.09 [8.26]	20.35 [5.60]	3.12	35	0.004*
MH5	22.19 [14.62]	17.31 [10.76]	4.28	35	<0.001*
HX	43.80 [16.34]	43.34 [14.14]	0.20	35	0.843
Pressure-time-integral (N/cm^{2}s)					
MH1	9.06 [3.45]	9.48 [3.36]	-1.04	35	0.308
MH2	12.23 [4.40]	11.80 [3.32]	1.40	35	0.171
MH3	11.33 [3.43]	10.72 [2.99]	2.03	35	0.050*
MH4	8.04 [3.04]	7.24 [2.29]	2.28	35	0.029*
MH5	7.02 [4.54]	5.88 [3.47]	2.91	35	0.006*
HX	10.47 [4.42]	10.50 [4.05]	-0.41	35	0.968
Contact time (% roll over process)					
MH1	79.43 [7.07]	81.75 [3.01]	-2.04	35	0.049*
MH2	81.91 [7.43]	84.08 [2.72]	-1.81	35	0.079
MH3	84.92 [6.10]	107.52 [12.82]	-1.06	35	0.298
MH4	83.04 [7.32]	85.19 [2.67]	-1.82	35	0.077
MH5	79.98 [7.44]	81.63 [3.96]	-1.24	35	0.224
HX	70.27 [9.78]	74.77 [9.05]	-2.47	35	0.019*
Maximum force (% body wt)					
MH1	23.23 [6.87]	25.03 [6.18]	-2.17	35	0.037*
MH2	24.97 [5.07]	24.86 [4.74]	0.23	35	0.820
MH3	23.30 [3.98]	22.22 [3.44]	1.87	35	0.070
MH4	14.68 [4.97]	13.19 [3.12]	2.71	35	0.010*
MH5	7.82 [3.40]	6.86 [2.48]	2.54	35	0.016*
HX	21.19 [7.82]	20.42 [6.96]	0.77	35	0.445
Force-time-integral ([% body wt]s)					
MH1	7.46 [2.56]	7.98 [2.06]	-1.66	35	0.106
MH2	8.56 [1.69]	8.49 [1.35]	0.30	35	0.763
MH3	8.15 [1.65]	7.94 [1.50]	0.76	35	0.451
MH4	5.33 [1.94]	4.81 [1.65]	2.43	35	0.021*
MH5	2.56 [1.26]	2.28 [1.04]	2.13	35	0.040*
HX	4.81 [2.19]	4.60 [1.84]	0.72	35	0.474

MH = metatarsal head, HX = hallux, * Sig. $p<0.05$, [ ] = SD

8.2.2 Hallux limitus plantar pressure measurement data

To assess for incremental changes to plantar pressure measurements over a 24-month period, recordings of peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral, for each hallux limitus subject were recorded pre-operation, and repeated at three, six, 12, 18 and 24-months post-operation. Not all subjects were available for follow-up measurements for each specified period of review. The ratio of *number-of-subjects-tested* to *number-of-subjects-in-group*, for each measurement period was as follows: Pre-operation (23:23), three-months (15:23), six-months (19:23), 12-months (22:23), 18-months (20:23) and 24-months (22:23). To complete the data for the purposes of statistical analysis, missing values were replaced with the mean score of the pressure variable for the period of assessment. Mean raw data with missing values are presented in Appendix H.

Multivariate analysis of variance was conducted to test for within-subject effects of time for the various pressure/force variables for the forefoot. The independent variable was time with six test-times over a two-year period. The six plantar loading dependent variables were the first-to-fifth metatarsal heads and the hallux. Assumption testing for univariate normality was conducted graphically, with histograms, stem-and-leaf plots, boxplots, normal probability and detrended normal plots, that demonstrated normality of data of all pressure/force variables. Similarly, Mahalanobis distance regression analysis failed to identify any multivariate outliers in any of the pressure/force variables (Coakes and Steed, 1999).

Overall there was a significant change of all pressure/force variables tested - peak pressure $F_{30,1070}=5.4$, $P<0.001$, pressure-time-integral $F_{30,545}= 3.6$, $P<0.001$; contact time $F_{30,545}= 3.2$, $P<0.001$; maximum force $F_{30,545}=4.2$, $P<0.001$; and force-time-integral $F_{30,545}=4.9$, $P<0.001$. Maulchly's test of sphericity showed assumptions of univariate normality were violated as sphericity for the variables could not be assumed, therefore Huynh-Feldt univariate tests were used to identify the region of the forefoot exhibiting significant plantar loading changes. Tests of within-subject contrasts were used to reveal between which measurement period the pressure changes occurred.

8.2.2.1 Peak pressure changes over time in the hallux limitus group

During the period of observation significant changes of peak pressure measurements were found to occur beneath the second, third, fifth metatarsal heads and the hallux. Descriptive statistics and univariate results with contrasts for hallux limitus subjects comparing successive measurement periods to assess peak pressure changes over time are presented in Table 8.4. Contrasts are presented only for those variables that showed a significant univariate result. Temporal changes to peak pressure of the forefoot are graphically presented in Figure 8.1.

With respect to the second, third and fifth metatarsal head regions, significant peak pressure change occurred in the initial three month post-operation period only. A considerable 35% increase in peak pressure was seen for the second metatarsal head, with approximately 16% increase for the third metatarsal. By comparison, a decrease in peak pressure for the fifth metatarsal head of 21% was seen. Peak pressure measurements of these metatarsal head regions were seen to stabilise following the initial three-month period. No significant changes were identified for the first and fourth metatarsal heads over the 24-month measurement period.

Peak pressure measurements of the hallux were seen to vary considerably. During the initial three month post-operation period, a significant decrease of 38% was noted, which continued to decrease slightly, although not significantly, for a further three months, when at six months a significant steady increase in peak pressure occurred until eighteen months post-operation. No significant differences in peak pressure measurements were found between pre- and post-operation values at 24-months.

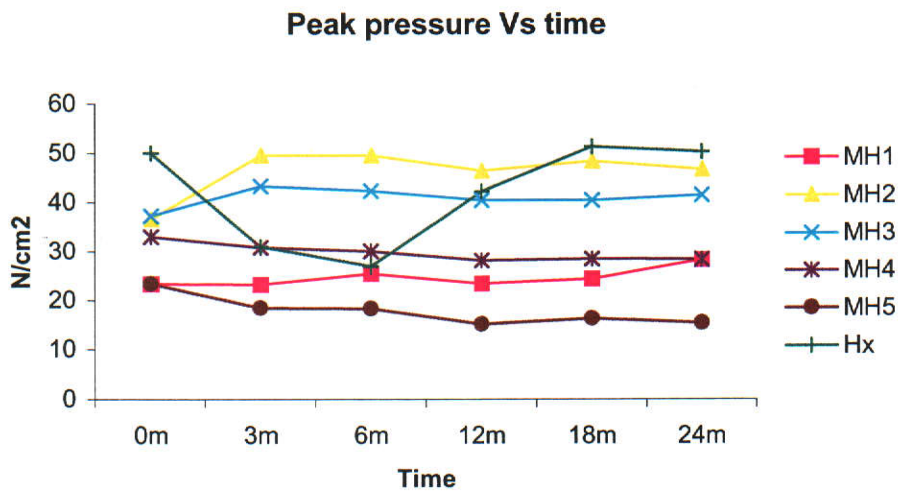
Univariate contrasts for mean peak pressure measurements between pre- and 24-months post-operation show that a significant increase for the second metatarsal while a significant decrease of the fifth metatarsal head area was found.

Table 8.4 Descriptive statistics (mean [SD]) and univariate results for peak pressure (N/cm^2) of hallux limitus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	23.40 [9.91]	23.23 [4.85]	25.49 [4.84]	23.46 [5.81]	24.42 [11.6]	28.30 [3.04]	1.49	3, 59	0.230
MH2	36.67 [11.04]	49.58 [15.85]	49.56 [15.23]	46.45 [17.53]	48.44 [16.50]	46.76 [3.14]	10.79	5, 108	0.001*
MH3	37.34 [9.70]	43.42 [7.83]	42.46 [6.58]	40.50 [11.16]	40.52 [9.28]	41.56 [2.51]	2.94	5, 100	0.019*
MH4	33.02 [12.25]	30.82 [5.82]	30.10 [8.14]	28.23 [10.47]	28.56 [10.28]	28.40 [2.46]	1.84	3, 71	0.142
MH5	23.44 [11.98]	18.38 [4.89]	18.31 [10.39]	15.11 [7.60]	16.27 [7.42]	15.32 [1.79]	5.73	4, 79	<0.001*
HX	50.09 [26.58]	31.03 [23.69]	27.03 [16.05]	42.30 [25.09]	51.36 [22.44]	50.29 [5.26]	8.23	5, 103	<0.001*

	Contrasts											
	0 - 3m F(1, 22)	p	3 - 6m F(1, 22)	p	6 - 12m F(1, 22)	p	12 - 18m F(1, 22)	p	18 - 24m F(1, 22)	p	0 - 24m F(1, 22)	p
MH2	37.18	<0.001*	0.00	0.990	2.11	0.160	0.74	0.400	1.74	0.200	24.32	<0.001*
MH3	10.58	0.004*	0.53	0.473	1.19	0.286	0.00	0.991	0.85	0.368	4.23	0.052
MH5	4.70	0.041*	0.00	0.973	2.18	0.154	2.04	0.167	0.70	0.411	18.07	<0.001*
HX	8.70	0.007*	0.57	0.459	15.27	0.001*	6.16	0.021*	0.06	0.806	0.01	0.974

MH = mctatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 8.1 Mean peak pressure measurements of the forefoot in hallux limitus subjects pre- and post-operation.

8.2.2.2 Overall peak pressure changes in hallux limitus group compared to control group

Control and hallux limitus mean peak pressures were compared at zero and 24-months post-operation by independent t-tests. As there were 36-subjects in the control group and only 23-subjects in the hallux limitus group, for the purposes of comparison, 23-subjects from the control group were randomly selected and compared to the hallux limitus subjects. Levene's test for equality of variance was used to test for homogeneity of variance for all pressure/force variables (Coakes and Steed, 1999). The results of the t-test indicate that only the fourth metatarsal was significantly higher in the hallux limitus group at zero and 24-months. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 8.5.

Table 8.5 Results of independent t-tests comparing control and hallux limitus groups at zero and 24-months for mean peak pressure (N/cm^2)

Time	Region	Mean Controls	Mean HL	Mean diff. Control-HL	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	28.57[10.88]	23.40 [9.91]	5.73	3.22	1.78	44	0.082
	MH2	40.66[15.57]	36.67[11.04]	4.43	4.07	1.09	44	0.282
	MH3	35.15[11.27]	37.34 [9.70]	-2.35	3.36	-0.70	44	0.487
	MH4	23.09 [8.26]	33.02[12.25]	-11.00	3.15	-3.49	44	0.001*
	MH5	22.19[14.62]	23.44[11.98]	0.11	4.23	0.03	44	0.979
	HX	43.80[16.34]	50.09[26.58]	-5.50	6.53	-0.84	44	0.405
24m	MH1	30.25 [9.05]	28.30 [3.04]	1.78	3.49	0.51	44	0.612
	MH2	40.14[14.46]	46.76 [3.14]	-4.67	4.50	-1.04	44	0.306
	MH3	33.67[11.31]	41.56 [2.51]	-7.36	3.71	-1.99	44	0.053
	MH4	20.35 [5.60]	28.40 [2.46]	-8.87	2.74	-3.25	44	0.002*
	MH5	17.31[10.76]	15.32 [1.79]	2.49	3.04	0.82	44	0.418
	HX	43.34[14.14]	50.29 [5.26]	-5.58	6.22	-0.90	44	0.375

HL = hallux limitus, MH = metatarsal head, HX = hallux, [ ] =std deviation, *sig difference, α=0.05

8.2.2.3 Pressure-time-integral changes over time in the hallux limitus group

As one would expect, pressure-time-integral findings were similar to those of peak pressure. During the period of observation only the second, third, fifth metatarsal head and hallux regions showed any significant changes. Descriptive statistics and univariate results with contrasts for hallux limitus subjects comparing successive measurement periods to assess peak pressure changes over time, as well as the pre-and 24-month measurements to assess the overall changes are presented in Table 8.6. Contrasts are presented only for those variables that showed a significant univariate result. Temporal changes to pressure-time-integral of the forefoot are graphically represented in Figure 8.2.

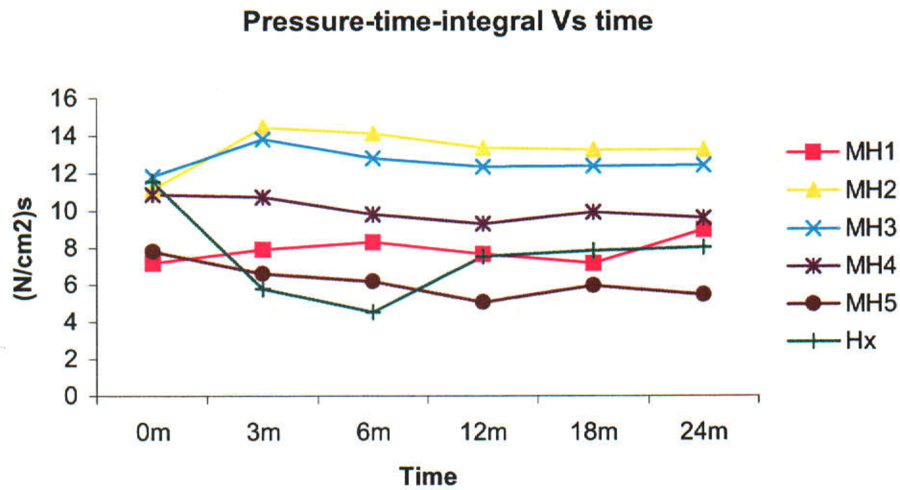
Immediately post-operation, the second and third metatarsal pressure-time-integral values increased over pre-operative recordings and stabilised by three months, recording no significant changes thereafter. The fifth metatarsal region showed a gradual decrease in value until the 12-month period, where there was a significant increase in value until the eighteen-month recording, which then stabilised to the pre-operative measurement.

Table 8.6 Descriptive statistics (mean [SD]) and univariate results for pressure-time-integrals ([N/cm^2]s) of hallux limitus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	7.19 [3.42]	7.93 [1.98]	8.32 [1.92]	7.69 [2.10]	7.19 [3.47]	9.00 [4.91]	1.84	2, 53	0.161
MH2	11.15 [3.04]	14.43 [3.96]	14.12 [4.73]	13.37 [5.19]	13.24 [4.75]	13.23 [4.65]	7.80	4, 93	<0.001*
MH3	11.86 [2.70]	13.82 [2.42]	12.83 [2.46]	12.38 [3.06]	12.41 [3.13]	12.43 [3.64]	3.14	4, 96	0.015*
MH4	10.88 [3.41]	10.73 [1.84]	9.82 [2.03]	9.31 [2.97]	9.92 [4.05]	9.64 [4.19]	1.83	3, 59	0.157
MH5	7.81 [3.43]	6.61 [1.75]	6.21 [2.98]	5.10 [2.51]	5.98 [2.64]	5.49 [2.94]	5.85	4, 83	<0.001*
HX	11.58 [6.95]	5.80 [4.69]	4.57 [3.11]	7.56 [5.46]	7.88 [4.93]	8.04 [4.42]	8.44	3, 67	<0.001*

	Contrasts											
	0 - 3m F(1, 22)	p	3 - 6m F(1, 22)	p	6 - 12m F(1, 22)	p	12 - 18m F(1, 22)	p	18 - 24m F(1, 22)	p	0 - 24m F(1, 22)	p
MH2	39.53	<0.001*	0.18	0.672	1.80	0.193	0.06	0.807	0.00	0.988	12.75	0.002*
MH3	13.53	0.001*	5.02	0.035*	0.99	0.331	0.00	0.946	0.00	0.954	0.95	0.339
MH5	3.60	0.071	0.57	0.459	2.62	0.120	5.80	0.025*	1.28	0.270	17.55	<0.001*
HX	11.04	0.003*	1.54	0.228	11.10	0.003*	0.16	0.696	0.04	0.837	6.11	0.022*

MH = metatarsal head, HX = hallux, *Significant at $p<0.05$



MH = metatarsal head, Hx = hallux

Figure 8.2 Mean pressure-time-integral measurements of the forefoot in hallux limitus subjects pre- and post-operation.

Pressure-time-integral measurements of the hallux were similar to peak pressure, in that an initial significant decrease was noted in the first three months, with a subsequent significant increase between six and 12-months.

Univariate contrasts for mean pressure-time-integral measurements between pre- and 24-months post-operation of the forefoot of hallux limitus subjects show an overall significant increase for the second metatarsal head, while significant decreases were found for the fifth metatarsal head and the hallux.

8.2.2.4 Overall pressure-time-integral changes in hallux limitus group compared to control group

Control and hallux limitus mean pressure-time-integrals were compared at zero and 24-months post-operation by paired t-test. The results reflect those found for peak pressure, with only the fourth metatarsal significantly higher at zero and 24-months. All other areas

Table 8.7 Results of independent t-tests comparing control and hallux limitus groups at zero and 24-months for mean pressure-time-integral ([N/cm^2]s)

Time	Region	Mean Controls	Mean HL	Mean diff. Control-HL	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	9.06 [3.45]	7.19 [3.42]	1.76	3.22	1.78	44	0.098
	MH2	12.23 [4.40]	11.15 [3.04]	0.66	4.07	1.09	44	0.525
	MH3	11.33 [3.43]	11.86 [2.70]	-0.95	3.36	-0.70	44	0.317
	MH4	8.04 [3.04]	10.88 [3.41]	-3.20	3.15	-3.49	44	0.002*
	MH5	7.02 [4.52]	7.81 [3.43]	-0.71	4.23	0.03	44	0.569
	HX	10.47 [4.42]	11.58 [6.95]	-1.29	6.53	-0.84	44	0.457
24m	MH1	9.48 [3.36]	9.00 [4.91]	-7.39E-02	1.16	-0.06	44	0.949
	MH2	11.80 [3.32]	13.23 [4.65]	-1.54	1.18	-1.30	44	0.200
	MH3	10.72 [2.99]	12.43 [3.64]	-1.98	1.03	-1.92	44	0.061
	MH4	7.25 [2.29]	9.64 [4.19]	-2.76	0.99	-2.78	44	0.008*
	MH5	5.88 [3.47]	5.49 [2.94]	0.33	0.97	0.34	44	0.739
	HX	10.50 [4.05]	8.04 [4.42]	2.48	1.28	1.93	44	0.060

HL = hallux limitus, MH = metatarsal head, HX = hallux, [ ] =std deviation, *sig difference, α=0.05

of the forefoot retained similar values between the two groups for both measurement periods. Changes to pressure-time-integral measurements for control and hallux limitus groups are shown in Table 8.7.

8.2.2.5 Contact time changes over time in the hallux limitus group

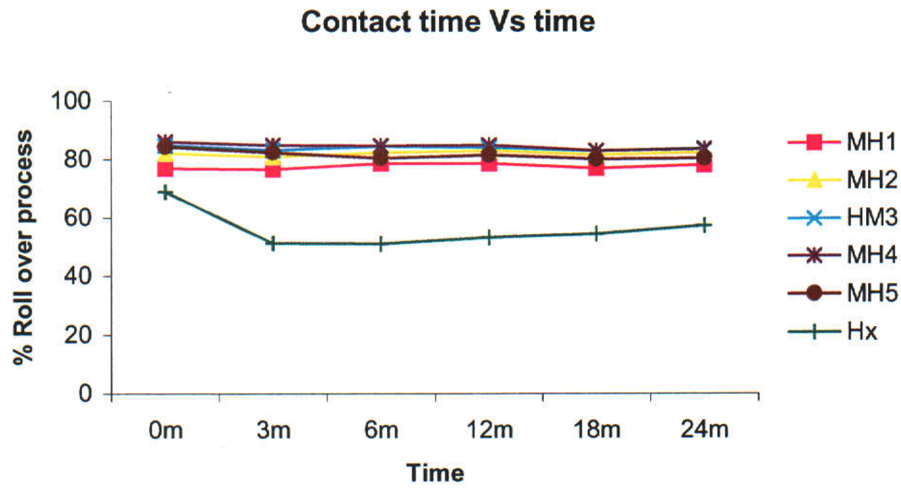
Contact time measurements for all plantar loading variables were relatively constant, with the exception of the fifth metatarsal head and hallux regions. Both areas showed significant initial decreases in contact time at the three-month period that remained significantly lower than pre-operative measurements for all subsequent periods. Descriptive statistics and univariate results with contrasts for hallux limitus subjects comparing successive measurement periods to assess contact time changes over time, as well as the pre-operative and 24-month measurements to assess the overall changes are presented in Table 8.8. Contrasts are presented only for those variables that showed significant univariate results. Temporal changes to contact time of the forefoot are graphically represented in Figure 8.3.

Table 8.8 Descriptive statistics (mean [SD]) and univariate results for contact time (% ROP) of hallux limitus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	77.03 [5.15]	76.57 [3.62]	78.49 [4.81]	78.67 [3.02]	76.91 [3.97]	77.97 [4.39]	1.64	5, 87	0.155
MH2	82.10 [3.67]	80.80 [2.74]	82.32 [3.87]	83.04 [2.86]	81.57 [3.18]	82.22 [3.49]	2.00	5, 110	0.084
MH3	84.87 [3.24]	83.28 [2.56]	84.61 [3.36]	84.23 [2.01]	82.93 [2.90]	83.78 [2.86]	2.15	4, 90	0.080
MH4	86.12 [3.44]	84.91 [2.06]	84.80 [4.28]	84.90 [2.97]	83.04 [3.72]	83.46 [3.66]	3.52	5, 100	0.007*
MH5	84.42 [4.32]	82.40 [3.41]	80.56 [7.37]	81.60 [5.11]	80.20 [6.03]	80.38 [6.36]	4.41	4, 85	0.003*
HX	69.10 [13.59]	51.30 [12.22]	51.09 [12.21]	53.30 [16.60]	54.47 [12.42]	57.36 [12.12]	10.04	5, 97	<0.001*

	Contrasts											
	0 - 3m F(1, 22)	p	3 - 6m F(1, 22)	p	6 - 12m F(1, 22)	p	12 - 18m F(1, 22)	p	18 - 24m F(1, 22)	p	0 - 24m F(1, 22)	p
MH4	3.24	0.085	0.01	0.909	0.01	0.907	4.21	0.052	0.36	0.553	10.28	0.004*
MH5	5.98	0.023*	2.16	0.156	1.08	0.310	1.71	0.205	0.30	0.862	10.62	0.004*
HX	31.46	<0.001*	0.01	0.940	0.62	0.440	0.20	0.663	2.77	0.110	10.05	0.004*

ROP = roll over process, MH = metatarsal head, HX = hallux, *Significant at $p<0.05$



MH = metatarsal head, Hx = hallux

Figure 8.3 Mean contact time measurements (% roll over process) of the forefoot in hallux limitus subjects pre- and post-operation.

Univariate contrasts for mean contact time measurements between pre- and 24-months post-operation of the forefoot of hallux limitus subjects showed an overall significant decrease for the fourth and fifth metatarsal heads and the hallux.

8.2.2.6 Overall contact time changes in hallux limitus group compared to control group

Control and hallux limitus mean contact time was compared at zero and 24-months post-operation by independent t-tests. The results indicate that contact time for the fifth metatarsal was initially significantly higher in the hallux limitus group, while at 24-months post-operation, measurements of the first, fourth metatarsals and hallux were significantly less than for the control group. Contact time for all other areas of the forefoot were essentially similar between the two groups for both measurement periods. Refer to Table 8.9.

Table 8.9 Results of independent t-test comparing control and hallux limitus groups at zero and 24-months for mean contact time (% ROP)

Time	Region	Mean Controls	Mean HL	Mean diff. Control-HL	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	79.43 [7.07]	77.03 [5.15]	2.01	1.82	1.10	44	0.277
	MH2	81.91 [7.43]	28.10 [3.67]	-0.62	1.68	-0.37	44	0.713
	MH3	84.92 [6.10]	84.87 [3.24]	-0.93	1.68	-0.56	44	0.583
	MH4	83.04 [7.32]	86.12 [3.44]	-3.36	1.70	-1.74	44	0.056
	MH5	79.98 [7.44]	84.42 [4.32]	-5.12	1.78	-1.98	44	0.006*
	HX	70.27 [9.78]	69.10[13.59]	1.16	3.59	-2.87	44	0.747
24m	MH1	81.75 [3.01]	77.97 [4.39]	3.78	1.16	3.25	44	0.002*
	MH2	84.08 [2.72]	82.22 [3.49]	1.78	0.91	1.96	44	0.056
	MH3	107.52[12.52]	83.78 [2.86]	35.95	33.43	1.07	44	0.294
	MH4	85.19 [2.67]	83.46 [3.66]	2.10	0.96	2.18	44	0.035*
	MH5	81.63 [3.96]	80.38 [6.36]	1.46	1.59	0.92	44	0.362
	HX	74.77 [0.05]	57.36[12.12]	18.43	3.26	5.66	44	<0.001*

HL = hallux limitus, MH = metatarsal head, HX = hallux, [ ] = standard deviation, ROP = roll over process, *sig difference, α=0.05

8.2.2.7 Maximum force changes over time in the hallux limitus group

The first metatarsal head is the only region where significant changes to mean maximum force were not found between any measurement period. The second metatarsal initially showed a significant increase that settled to pre-operation values by the six-month period. Measurements of the third metatarsal area showed slight but significant decrease in maximum force over the three to 12-month periods, which resumed pre-operative values by 18-months. By contrast, the fourth and fifth metatarsal regions had small but significant changes over the six to 24-months, with a resultant significant overall decrease in the pre to post-operation values.

Descriptive statistics and univariate results with contrasts for hallux limitus subjects comparing successive measurement periods to assess peak pressure changes over time, together with the pre- and 24-months post-operative measurements to assess for overall changes are presented in Table 8.10. Contrasts are presented only for those variables that showed significant univariate results. Temporal changes to maximum force of the forefoot are graphically represented in Figure 8.4.

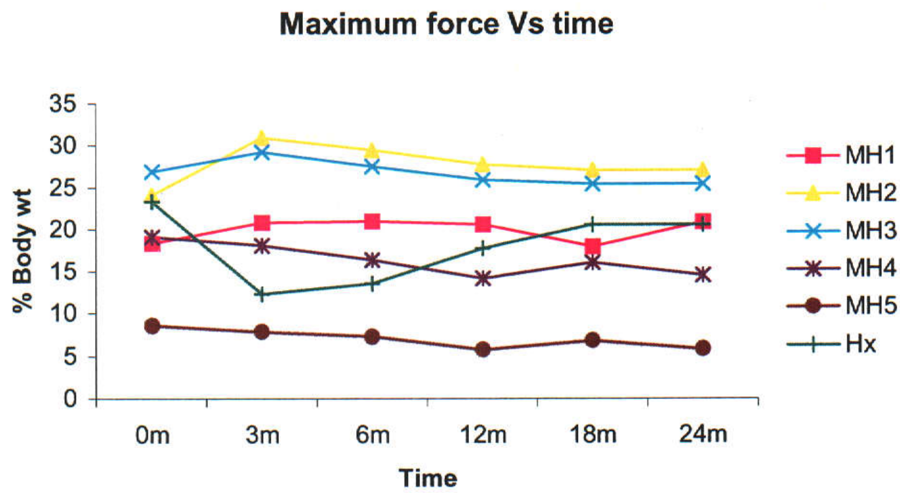
Table 8.10 Descriptive statistics (mean [SD]) and univariate results for maximum force (% body wt) of hallux limitus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	18.36 [6.70]	20.89 [4.14]	21.02 [6.31]	20.64 [5.23]	17.98 [5.43]	20.95 [6.59]	1.85	5, 110	0.110
MH2	24.14 [5.03]	30.93 [6.01]	29.50 [4.45]	27.75 [5.20]	27.06 [5.02]	27.07 [4.39]	7.92	4, 93	<0.001*
MH3	26.93 [5.27]	29.29 [3.77]	27.57 [4.26]	26.00 [4.26]	25.51 [2.91]	25.46 [3.99]	5.20	4, 84	0.001*
MH4	19.15 [5.57]	18.11 [4.38]	16.39 [4.86]	14.17 [3.90]	16.07 [3.62]	14.54 [3.87]	7.99	4, 100	<0.001*
MH5	8.62 [3.32]	7.88 [2.51]	7.32 [3.80]	5.76 [2.12]	6.80 [2.37]	5.83 [2.16]	7.02	4, 100	<0.001*
HX	23.41[10.49]	12.31 [5.39]	13.59 [6.22]	17.80 [7.25]	20.64 [9.16]	20.60 [9.06]	10.66	4, 99	0.004*

Contrasts

	0 - 3m F(1, 22)	p	3 - 6m F(1, 22)	p	6 - 12m F(1, 22)	p	12 - 18m F(1, 22)	p	18 - 24m F(1, 22)		0 - 24m F(1, 22)	p
MH2	25.17	<0.001*	0.99	0.331	1.97	0.174	0.40	0.535	0.00	0.977	8.73	0.007*
MH3	3.38	0.080	6.36	0.019*	4.42	0.047*	0.48	0.497	0.01	0.945	1.65	0.212
MH4	0.62	0.439	3.36	0.081	6.88	0.016*	5.99	0.023*	5.96	0.023*	19.40	<0.001*
MH5	1.15	0.296	0.91	0.351	4.32	0.050*	6.13	0.021*	6.65	0.017*	18.04	<0.001*
HX	18.98	<0.001*	0.64	0.433	11.15	0.003*	2.32	0.142	0.00	0.985	1.58	0.221

MH = metatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 8.4 Mean maximum force measurements of the forefoot in hallux limitus subjects pre- and post-operation.

As for peak pressure, maximum force of the hallux showed a significant decrease during the initial three-month period that increased significantly between six and 12-months to remain at levels similar to pre-operative values. Univariate contrasts for mean maximum force measurements between pre- and 24-months post-operation of the forefoot of hallux limitus subjects show a small but significant increase of the second metatarsal, while similar significant decreases were found for the third, fourth and fifth metatarsal heads.

8.2.2.8 Overall maximum force changes in hallux limitus group compared to control group

Control and hallux limitus mean maximum force was compared at zero and 24-months post-operation by independent t-tests. The results indicate that maximum force was significantly higher in the hallux limitus group for the first metatarsal, and significantly lower for the third and fourth metatarsals, pre- and post-operatively. There were no significant differences between control and hallux limitus groups for any other forefoot region at either measurement period. Refer to Table 811.

Table 8.11 Results of independent t-tests comparing control and hallux limitus groups at 0 and 24-months for mean maximum force (% body wt)

Time	Region	Mean Controls	Mean HL	Mean diff. Control-HL	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	23.23 [6.87]	18.36 [6.70]	5.60	2.07	2.70	44	0.010*
	MH2	24.97 [5.07]	24.14 [5.03]	0.79	1.66	0.48	44	0.636
	MH3	23.30 [3.98]	26.93 [5.27]	-4.96	1.34	-3.70	44	0.001*
	MH4	14.68 [4.97]	19.15 [5.57]	-5.54	1.42	-3.91	44	<0.001*
	MH5	7.82 [3.40]	8.62 [3.32]	-0.91	0.93	-0.98	44	0.332
	HX	21.19 [7.82]	23.41 [10.49]	-2.86	2.84	-1.01	44	0.318
24m	MH1	25.03 [6.18]	20.95 [6.59]	5.12	1.94	2.64	44	0.011*
	MH2	24.86 [4.74]	27.07 [4.39]	-1.95	1.47	-1.32	44	0.192
	MH3	22.22 [3.44]	25.46 [3.99]	-4.21	1.09	-3.86	44	<0.001*
	MH4	13.19 [3.12]	14.54 [3.87]	-2.31	0.90	-2.58	44	0.015*
	MH5	6.86 [2.48]	5.83 [2.16]	0.93	0.60	1.52	44	0.135
	HX	20.42 [6.96]	20.60 [9.06]	-0.66	2.46	-0.27	44	0.789

HL = hallux limitus, MH = metatarsal head, HX = hallux, [ ] =std deviation, *sig difference, α=0.05

8.2.2.9 Force-time-integral changes over time in the hallux limitus group

All dependent variables showed significant force-time-integral changes during the overall period of measurement. The first metatarsal had a period of significant increased values between 18 and 24-months, with an overall significant increased measurement between zero and 24-months. The second and third metatarsal regions had similar significant initial increases between zero and three months, with the second metatarsal region stabilised at significantly higher levels at 24-months compared with pre-operative values. The third metatarsal head also stabilised at similar levels by 24-months to pre-operative measurements.

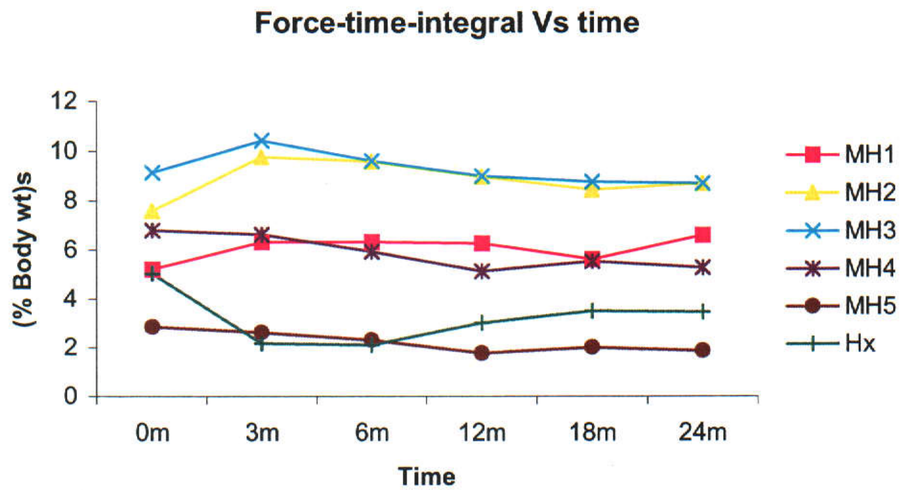
Descriptive statistics and univariate results with contrasts for hallux limitus subjects comparing successive measurement periods to assess force-time-integral changes over time, as well as the pre-and 24-month measurements to assess the overall changes are presented in Table 8.12. Contrasts are presented only for those variables that showed a significant univariate result. Temporal changes to force-time-integral of the forefoot are graphically represented in Figure 8.5.

Table 8.12 Descriptive statistics (mean [SD]) and univariate results for force-time-integrals ([% body wt]s) of hallux limitus subjects 0-24 months post-operation

	Time (months) 0	3	6	12	18	24	F	df	p
MH1	5.22 [2.12]	6.31 [1.69]	15.63 [3.41]	6.26 [1.79]	5.62 [1.88]	6.58 [2.44]	2.82	4, 100	0.023*
MH2	7.58 [1.55]	9.76 [1.41]	6.32 [2.13]	8.97 [1.72]	8.45 [1.31]	8.69 [1.39]	10.84	5, 86	<0.001*
MH3	9.16 [1.64]	10.44 [1.12]	9.57 [1.28]	9.01 [1.49]	8.77 [1.22]	8.72 [1.24]	8.68	4, 82	<0.001*
MH4	6.80 [1.99]	6.63 [1.41]	9.63 [1.38]	5.13 [1.40]	5.54 [1.73]	5.28 [1.56]	8.76	4, 88	<0.001*
MH5	2.87 [1.09]	2.63 [0.87]	5.94 [1.61]	1.79 [0.76]	2.03 [0.86]	1.87 [0.76]	11.21	4, 91	<0.001*
HX	5.05 [2.59]	2.18 [1.25]	2.32 [1.06]	3.03 [1.72]	3.53 [1.89]	3.47 [1.99]	13.10	3, 76	<0.001*

	Contrasts 0 - 3m F(1,22)	p	3 - 6m F(1,22)	p	6 - 12m F(1,22)	p	12 - 18m F(1,22)	p	18 - 24m F(1,22)	p	0 – 24m F(1, 22)	p
MH1	4.24	0.051	0.00	0.989	0.02	0.900	3.01	0.097	5.06	0.035*	8.70	0.007*
MH2	33.25	<0.001*	0.24	0.632	2.74	0.112	2.65	0.118	1.31	0.264	8.99	0.007*
MH3	10.70	0.003*	9.80	0.005*	4.47	0.046*	1.31	0.264	0.06	0.816	1.20	0.285
MH4	0.18	0.675	8.27	0.009*	7.47	0.012*	2.76	0.111	1.88	0.184	13.73	0.001*
MH5	1.31	0.264	3.59	0.071	6.56	0.018*	6.96	0.015*	1.40	0.249	19.82	<0.001*
HX	20.08	<0.001*	0.03	0.860	9.58	0.005*	2.44	0.133	0.06	0.816	9.25	0.006*

MH = metatarsal head, HX = hallux, *Significant at $p<0.05$



MH = metatarsal head, Hx = hallux

Figure 8.5 Mean force-time-integral measurements of the forefoot in hallux limitus subjects pre- and post-operation.

Force-time-integral values for the fourth metatarsal head area showed significant decreases between three and 12-months with an overall significant reduction in measurement at 24-months compared with the pre-operative values. Similar findings were seen for the fifth metatarsal region, with a significant decrease between six and 12 months and a subsequent significant increase between 12 and 18-months, to yield an overall significant decrease between pre- and post-operative measurements. The hallux showed an initial significant decrease over the first three months with a subsequent significant increase over the six to 18-month period, to stabilise by 24-months at significantly lower than pre-operative values.

8.2.2.10 Overall force time-integral changes in hallux limitus group compared to control group

Control and hallux limitus mean force-time-integral was compared at zero and 24-months post-operation by paired t-tests. The results largely parallel those for maximum force, indicating that force-time-integral was significantly higher in the hallux limitus group for

Table 8.13 Results of independent t-tests comparing control and hallux limitus groups at zero and 24-months for mean force-time-integral ([% body wt])s

Time	Region	Mean Controls	Mean HL	Mean diff. Control-HL	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	7.46 [2.56]	5.22 [2.12]	2.28	0.74	3.08	44	0.004*
	MH2	8.56 [1.69]	7.58 [1.55]	0.73	0.49	1.47	44	0.148
	MH3	8.15 [1.65]	9.16 [1.64]	-1.50	0.44	-3.42	44	0.001*
	MH4	5.33 [1.94]	6.80 [1.99]	-1.94	0.53	-3.64	44	0.001*
	MH5	2.56 [1.26]	2.87 [1.09]	-0.40	0.32	-1.24	44	0.220
	HX	4.81 [2.19]	5.05 [2.59]	-0.45	0.74	-0.61	44	0.544
24m	MH1	7.98 [2.06]	6.58 [2.44]	1.27	0.62	2.04	44	0.047*
	MH2	8.49 [1.35]	8.69 [1.39]	-0.41	0.42	-0.96	44	0.340
	MH3	7.94 [1.50]	8.72 [1.24]	-1.30	0.38	-3.47	44	0.001*
	MH4	4.81 [1.65]	5.28 [1.56]	-0.93	0.38	-2.41	44	0.020*
	MH5	2.28 [1.04]	1.87 [0.76]	0.26	0.22	1.20	44	0.235
	HX	4.60 [1.84]	3.47 [1.99]	0.89	0.56	1.58	44	0.121

HL = hallux limitus, MH = metatarsal head, HX = hallux, [ ] =std deviation, *sig difference, α=0.05

the first metatarsal, and significantly lower for the third and fourth metatarsals, pre- and post-operation. There were no significant differences between control and hallux limitus groups of any other forefoot region at either measurement period. Refer to Table 8.13.

8.2.2.11 Summary of overall changes of pressure/force variables of hallux limitus group

A summary of the overall significant plantar pressure measurement changes between the pre- and 24-month post-operation status for hallux limitus subjects is presented in Table 8.14. Importantly, pressure/force variables to the second metatarsal head show significantly increased post-operative load. Decreases of most pressure/force variables to the fifth metatarsal head may suggest the post-operative hallux limitus foot functions in a less supinated manner compared to pre-operatively. Interestingly, although the surgery involved an osteotomy of the first metatarsal head, no apparent changes to peak pressure of the first metatarsal head and hallux, or maximum force of the hallux were identified.

Table 8.14 Univariate contrasts and relative changes of significant plantar pressure changes pre- and 24-months post-operation in hallux limitus subjects

	Region	F(1,22)	*P*	% Change
Peak pressure	MH2	4.78	<0.001	28% ↑
	MH5	18.08	<0.001	37% ↓
Pressure-time-integral	MH2	12.75	0.002	19% ↑
	MH5	17.55	<0.001	30% ↓
	HX	6.11	0.022	31% ↓
Contact time	MH5	10.62	0.004	5% ↓
	HX	10.05	0.004	17% ↓
Maximum force	MH2	8.73	0.007	12% ↑
	MH4	19.40	<0.001	24% ↓
	MH5	18.04	<0.001	32% ↓
Force-time-integral	MH1	8.70	0.007	26% ↑
	MH2	8.99	0.007	15% ↑
	MH4	13.73	<0.001	22% ↓
	MH5	19.82	<0.001	35% ↓
	HX	9.25	0.006	31% ↓

MH = metatarsal head, HX = hallux

8.2.3 Range of motion of first metatarsophalangeal joint

The passive range of motion of the hallux at the first metatarsophalangeal joint was examined with the foot in a non-weight bearing relaxed position pre-operation and at 24-months post-operation in the hallux limitus group. To test intra-rater reliability of measurement of the hallux, passive dorsiflexion and plantarflexion motions of six-control subjects were recorded three times at random and intraclass correlation coefficients (ICC) calculated. The ICC's for measurement of the hallux were found to be good, with dorsiflexion = 0.96 ($F_{5,10}$=54.76, P<0.001) and plantarflexion = 0.84 ($F_{5,10}$=14.17, P<0.001), in accordance with Portney and Watkins (1993). Refer to Appendix J for raw data used to examine the intra-rater reliability of measurement of first metatarsophalangeal joint motion, and Appendix K for raw data of range of motion of hallux in hallux limitus subjects.

Table 8.15 Descriptive statistics of mean passive range of motion of hallux and paired t-test results in hallux limitus subjects pre- and 24-months post-operation

	Pre-operation	24mnths Post-op	Change	t	df	Sig. (2-tailed)
Plantarflexion	10.8° [8.6°]	7.6° [11.7°]	-3.2°	1.45	22	0.160
Dorsiflexion	30.8° [10.2°]	60.1° [14.0°]	29.3°	-17.62	22	<0.001
Total ROM	41.2° [16.2°]	68.5° [22.9°]	27.3°	-7.90	22	<0.001

ROM = range of motion, [ ] = SD

A paired sample t-test was conducted and showed significant increases in dorsiflexion and total range of motion of the hallux. This finding demonstrated a considerable increase in total range of motion of the hallux, to normal values, due to clinical improvement in the range of dorsiflexion available post-operatively. See Table 8.15.

8.2.3.1 Correlation of pressure measurements with range of motion of hallux

Pearson correlation matrices were generated to assess the relationship between plantar pressure measurements and the passive range of motion of the hallux at the first metatarso-phalangeal joint. See Table 8.16.

With respect to pre-operative peak pressure, there was a moderate negative correlation between the measured dorsiflexion/total range of motion with peak pressure of the fifth metatarsal head. At 24-months post-operation, there was a strong negative correlation between the amount of plantarflexion and peak pressure of the first metatarsal. A moderate negative correlation was also found between dorsiflexion/total range of motion of the hallux and peak pressure of the third and fourth metatarsal heads.

With respect to pressure-time-integral, no significant correlations were found between hallucal dorsiflexion and measurements at any forefoot region. However at 24-months post-operation, a moderate negative correlation was found to exist between dorsiflexion of the hallux and pressure-time-integral of the first metatarsal head.

Table 8.16 Correlation of plantar pressure measurements with range of motion of hallux at pre- and 24-months post-operation

		Pre-operation		24-months post-operation		
		Pearson Corr.	Sig. (2-tailed)	Pearson Corr.	Sig. (2-tailed)	N
Peak pressure						
MH1	ROM	-0.192	0.380	-0.409	0.053	23
	DF	0.016	0.941	-0.184	0.400	
	PF	-0.415*	0.049	-0.581**	0.004	
MH2	ROM	-0.047	0.831	-0.140	0.524	23
	DF	0.080	0.715	-0.079	0.720	
	PF	-0.241	0.267	-0.180	0.410	
MH3	ROM	-0.294	0.173	-0.558**	0.006	23
	DF	-0.198	0.365	-0.536**	0.008	
	PF	-0.400	0.058	-0.452*	0.030	
MH4	ROM	-0.365	0.087	-0.580**	0.004	23
	DF	-0.351	0.101	-0.624**	0.001	
	PF	-0.331	0.123	-0.390	0.066	
MH5	ROM	-0.587**	0.003	-0.373	0.080	23
	DF	-0.559**	0.006	-0.387	0.068	
	PF	-0.442*	0.035	-0.267	0.217	
HX	ROM	-0.039	0.860	-0.044	0.843	23
	DF	0.014	0.949	-0.132	0.549	
	PF	-0.127	0.564	0.073	0.742	
Pressure-time-integral						
MH1	ROM	-0.186	0.395	-0.338	0.114	23
	DF	-0.025	0.910	-0.110	0.617	
	PF	-0.420*	0.046	-0.532**	0.009	
MH2	ROM	-0.121	0.583	-0.124	0.574	23
	DF	-0.004	0.986	-0.060	0.787	
	PF	-0.294	0.173	-0.172	0.434	
MH3	ROM	-0.343	0.109	-0.431*	0.040	23
	DF	-0.249	0.252	-0.392	0.065	
	PF	-0.443	0.034	-0.376	0.077	
MH4	ROM	-0.391	0.065	-0.483*	0.020	23
	DF	0.274	0.205	-0.478	0.021	
	PF	-0.406	0.055	-0.374	0.079	
MH5	ROM	-0.593**	0.003	-0.400	0.059	23
	DF	-0.140	0.523	-0.395	0.062	
	PF	-0.485*	0.019	-0.312	0.148	
HX	ROM	0.000	0.085	0.405	0.056	23
	DF	0.085	0.699	0.277	0.201	
	PF	-0.140	0.523	0.462*	0.026	

Table 8.16 continued

Contact time						
MH1	ROM	0.264	0.223	-0.099	0.653	23
	DF	-0.013	0.955	-0.013	0.955	
	PF	-0.180	0.412	-0.180	0.412	
MH2	ROM	-0.228	0.295	-0.313	0.146	23
	DF	-0.268	0.215	-0.268	0.215	
	PF	-0.293	0.176	-0.293	0.176	
MH3	ROM	0.230	0.290	-0.355	0.096	23
	DF	-0.320	0.137	-0.320	0.137	
	PF	-0.314	0.145	-0.314	0.145	
MH4	ROM	0.028	0.900	-0.241	0.267	23
	DF	-0.318	0.139	-0.318	0.139	
	PF	0.594**	0.003	-0.092	0.676	
MH5	ROM	-0.068	0.759	-0.024	0.913	23
	DF	0.111	0.616	-0.131	0.550	
	PF	0.361	0.096	0.111	0.616	
HX	ROM	0.104	0.637	0.684**	<0.001	23
	DF	0.212	0.331	0.532**	0.009	
	PF	-0.063	0.774	0.706**	<0.001	
Maximum force						
MH1	ROM	0.052	0.813	-0.244	0.262	23
	DF	0.162	0.460	-0.077	0.727	
	PF	-0.089	0.686	-0.387	0.068	
MH2	ROM	0.219	0.316	0.052	0.812	23
	DF	0.089	0.688	0.051	0.816	
	PF	0.324	0.131	0.041	0.851	
MH3	ROM	0.089	0.290	-0.663**	0.001	23
	DF	-0.148	0.500	-0.728**	<0.001	
	PF	0.319	0137	-0.429*	0.041	
MH4	ROM	0.028	0.900	-0.546	0.007	23
	DF	-0.400	0.059	-0.640**	0.001	
	PF	-0.066	0.766	-0.302	0.161	
MH5	ROM	-0.068	0.759	-0.281	0.193	23
	DF	-0.459	0.027	-0.325	0.130	
	PF	-0.163	0.457	-0.163	0.459	
HX	ROM	0.104	0.637	0.395	0.062	23
	DF	0.185	0.399	0.384	0.070	
	PF	0.186	0.395	0.315	0.143	

Table 8.16 continued

Force-time-integral

MH1	ROM	0.029	0.896	-0.188	0.391	23
	DF	0.181	0.409	0.096	0.663	
	PF	-0.173	0.430	-0.484*	0.019	
MH2	ROM	0.144	0.511	0.001	0.997	23
	DF	0.044	0.841	0.106	0.632	
	PF	0.216	0.323	-0.125	0.568	
MH3	ROM	0.028	0.901	-0.622**	0.002	23
	DF	-0.202	0.356	-0.633**	0.001	
	PF	0.262	0.228	-0.461*	0.027	
MH4	ROM	-0.233	0.284	-0.560**	0.005	23
	DF	-0.304	0.112	-0.593**	0.003	
	PF	-0.068	0.758	-0.388	0.067	
MH5	ROM	-0.326	0.129	-0.290	0.180	23
	DF	-0.390	0.066	-0.330	0.125	
	PF	-0.126	0.567	-0.173	0.429	
HX	ROM	0.258	0.234	0.641**	0.001	23
	DF	0.268	0.216	0.602**	0.002	
	PF	0.171	0.436	0.536**	0.008	

PF = plantarflexion DF = dorsiflexion ROM = total range of motion of hallux, MH = metatarsal head, HX = hallux, *Significant at 0.05 level, ** Significant at 0.001 level.

For contact time, there was a moderate positive correlation between plantarflexion of the hallux and the fourth metatarsal head. At 24-months there was a moderate positive correlation between both plantarflexion and dorsiflexion of the hallux and contact time of the hallux.

No significant correlation was seen between maximum force of any forefoot region and hallucal motion pre-operatively. However, post-operatively there was a strong negative correlation between the amount of dorsiflexion of the hallux and maximum force with the third and fourth metatarsal head. Similarly, no significant correlation was found between hallucal motion and force-time-integral pre-operation. However, a moderate negative correlation was found between dorsiflexion and the third and fourth metatarsal heads, while a moderate positive correlation was found for both dorsiflexion and plantarflexion and force-time-integral of the hallux.

8.2.4 Summary of results of hallux limitus data

Plantar pressure measurements in the group of 23-hallux limitus subjects studied demonstrated a significant decrease in all pressure/force variables of the hallux at three months post-operation. Peak pressure initially fell at three months, stabilised at six months and then returned to pre-operative levels by 18-months. Similarly, pressure-time-integral and contact time significantly dropped by three months from pre-operation measures to increase significantly between three and six months for pressure-time-integral and six and 12-months for contact time, to stabilise at significantly lower than pre-operative levels. Maximum force and force-time-integral measurements of the hallux largely paralleled pressure measurement trends and showed significantly lower levels at 24-months compared to pre-operation values.

Interestingly, despite the fact that the Youngswick procedure is designed to shorten and plantar-flex the first metatarsal head, this area showed no significant changes in peak pressure, pressure-time-integral, contact time or maximum force between any measurement period or between the pre- and 24-months post-operative measurements. Only force-time-integral measurements showed a slight significant increase at three months and a similar increase between 18 and 24-months to remain slightly higher than pre-operative levels.

The second metatarsal head showed significant increases over the initial three-month period for all dependant variables except for contact time, remaining at higher levels at 24-months compared to pre-operative values. This finding may be of long-term clinical significance, raising the potential possibility of developmental iatrogenic metatarsalgia. The third metatarsal head region showed initial significant increases in all pressure/force variables except contact time, similar to the second metatarsal head. These initially elevated values gradually decreased by 12-months to pre-operative levels, although remaining significantly higher than the mean value for the control group.

Pressure measurements for the fourth and fifth metatarsal regions showed significant but small fluctuations over the measurement period, with an overall significant decrease by

24-months compared to pre-operative measurements, except for pressure-time-integral for the fourth metatarsal, which remained unchanged at a significantly higher level than the control group. Representative two and three-dimensional EMED footprints demonstrating peak pressure distribution of a typical hallux limitus subject, pre- and 24-months post-operation, are illustrated in Figures 8.6 and 8.7.

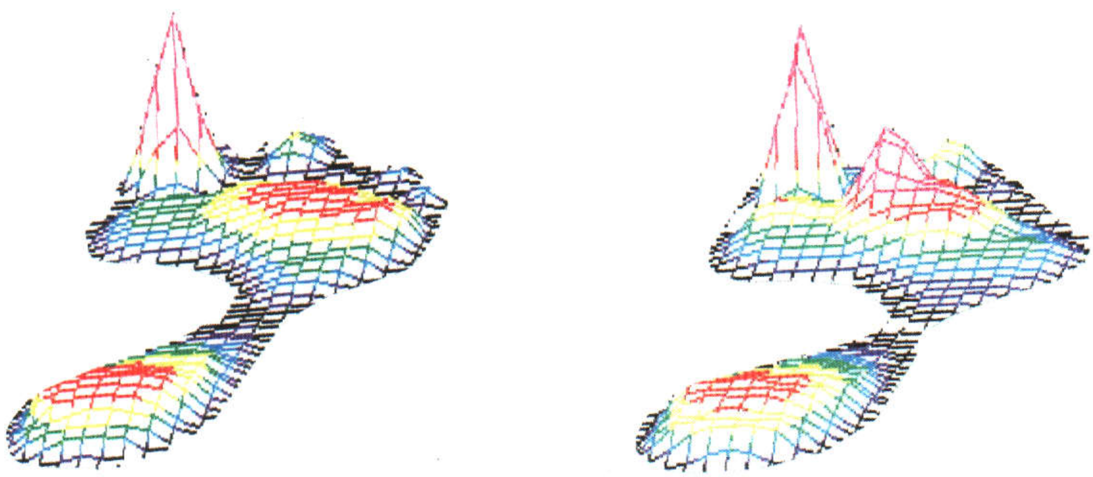
An explanation of these findings is suggested in the correlation results between pressure variables and range of motion of the hallux. The dorsiflexion range of motion of the hallux that was found to improve to near normal values post-operatively and be negatively correlated with the pre-operative peak pressure measurements of the fourth and fifth metatarsal heads. Similarly, the amount of post-operative hallucal dorsiflexion is negatively correlated with maximum force and force-time-integral of the fourth metatarsal head. In other words, limitation of dorsiflexion of the hallux due to the presence of peri-articular osteophytes and other structural factors that define the condition, may cause the foot to function in a more supinated manner or possibly more externally rotated position, placing increased load on the lateral metatarsals. Post-operatively, the amount of available dorsiflexion of the hallux is increased, that may lead to a reduction of foot supination or function in a less externally rotated position, decreasing the lateral loading of the forefoot.

It has been demonstrated that plantar pressure measurements following the Youngswick procedure for the treatment of hallux limitus largely affect the hallux, second, fourth and fifth metatarsal areas. Initially the hallux experiences significant decreases in pressure variables, contact time and force variables that stabilise by 12-months at slightly reduced, or in the case of peak pressure, at similar to pre-operative levels. The second metatarsal area concurrently experiences a significant initial increase in pressure/force variables that rapidly stabilises by six months to significantly higher than pre-operative measurements. Although post-operation radiographs were not taken of hallux limitus subjects, the most likely cause of the long-term increased pressure beneath the second metatarsal is first metatarsal shortening associated with the surgical procedure. The most plausible cause of

Pre-operation

24 months post-operation

Figure 8.6 Two-dimensional images of maximum pressure pictures of hallux limitus subject # 13



Pre-operation

24 months post-operation

Figure 8.7 Three-dimensional images of maximum pressure pictures of subject # 13 decreased loading of the lateral forefoot is an increase in the amount of available dorsiflexion of the hallux allowing the foot to function in a less supinated position.

In conclusion, with respect to plantar pressure distribution, podiatric surgery of the type used in this study to treat hallux limitus produced significant immediate post-operative changes to plantar pressure distribution that appear to stabilise with improved first metatarsophalangeal joint motion over a 12 to18-month period. Although a number of pressure/force variables of some regions of the forefoot do change from being significantly different pre-operatively to approximate normal values by 24-months post-operation, many variables at various regions become or remain significantly different post-operatively. Therefore, the hypothesis that plantar pressure measurements of feet with hallux limitu change to approximate normal values following the Youngswick procedure is rejected.

Finally, the Youngswick operation was shown to produce a significant increase in the range of motion the first metatarsophalangeal joint of the foot in hallux limitus patients to normal levels. Therefore, the hypothesis that the Youngswick procedure will produce improved range of motion of the hallux at the first metatarsophalangeal joint to normal values is accepted.

8.3 DISCUSSION

Plantar pressure measurements of 36 normal control subjects were made at zero and 24-months. Twenty-three subjects with symptomatic grade I or II hallux deformity were assessed pre-operatively and plantar pressure measurements were made at numerous intervals over a 24-month period following surgery. A pre- and post-operative range of motion study of the first metatarsophalangeal joint was also undertaken.

With respect to subject demographics, the control group represented a more homogenous gender balance, while a female bias was seen in the hallux limitus group. The mean age and body mass index of the control group was less than the hallux limitus group, however these factors were not found to correlate with any pressure variable tested in the control group. Therefore, given the relatively modest differences involved and the absence of any demonstrable effect in the control group, age and gender differences are unlikely to have adversely effected pressure measurements in the hallux limitus group.

8.3.1 Plantar pressure measurement changes to hallux limitus group

To the authors knowledge there have been no studies published investigating the effects of first metatarsophalangeal joint surgery (Youngswick osteotomy/cheilectomy or similar procedure) on plantar pressure distribution within the forefoot. At the time of writing, only three studies have been reported in the literature outlining the effects of pressure distribution following surgery for hallux limitus (Stuck et al, 1988; Samnegard et al, 1991; Southgate & Urry, 1997). Given that the surgery performed in each study was essentially different to that performed on this group of hallux limitus subjects, and that the pressure measuring equipment and methodology used varied, only broad comparisons should be made between the results. Table 8.17 summarises the main findings of previously published reports of plantar pressure changes following hallux limitus surgery.

The Youngswick procedure for the correction of hallux limitus involves removing peri-articular osteophytes to increase the first metatarsophalangeal joint dorsiflexion range of motion and a space reduction osteotomy to shorten the first metatarsal and lower the metatarsal head relative to the shaft to 'decompress' the joint. Accordingly, it might be expected that plantar pressure measurement changes would occur in the forefoot over time following surgical intervention, particularly in the medial forefoot.

The normal post-operative clinical progress following the Youngswick procedure is for the first metatarsal osteotomy to heal within two-three months, which usually corresponds with an increasing ability to wear regular shoes and to commence ambulatory exercise programs, such as walking for fitness (Bryant, 1996).

Plantar pressure measurements in the group of subjects studied demonstrated a significant decrease in all pressure/force variables of the hallux at three months post-operation. Peak

Table 8.17 Previously reported plantar pressure changes following hallux limitus surgery

Author	Equipment	Type of surgery	No subjects	Finding
Stuck et al, (1988)	EDG	Implant arthroplasty	5	↓ CT HX
Samnegard et al, (1991)	EMED	Keller arthroplasty Arthrodesis	10 10	↑ PP midfoot ↑ PP midfoot
Southgate & Urry (1997)	Musgrave	Hallucal osteotomy Arthrodesis	10 20	↑ PP MH1 ↑ CT HX

MH = metatarsal head, HX = hallux, CT = contact time, PP = peak pressure

pressure initially falls at three months, stabilises to six months and then begins to return to pre-operative levels by eighteen months post-operation. Similarly, pressure-time-integral and contact time significantly drops at three months from pre-operative measures to increase significantly between three and six months for the pressure integrals and six and twelve months for contact time, and to stabilise at significantly lower than pre-operative levels. Maximum force and force-time-integral measurements of the hallux largely paralleled pressure measurement trends that show significantly lower levels at 24-months compared with pre-operative values.

Interestingly, despite the fact that the Youngswick osteotomy/cheilectomy is designed to shorten and plantar-flex the first metatarsal head, this area showed no significant changes in peak pressure, pressure-time-integral, contact time or maximum force neither between any measurement period nor between the pre- and 24-months post-operation measurements. Only force-time-integral measurements showed a slight significant increase at three months and a similar increase between 18 and 24-months to remain slightly higher than pre-operation levels.

The second metatarsal head showed significant increases over the initial three-month period for all dependent variables except for contact time, which remained at higher levels at 24-months compared with pre-operative values. This finding is consistent with that of Samnegard et al. (1991), who using an EMED system, also found higher peak pressures in the central forefoot following Keller arthroplasty and first metatarsophalangeal arthrodesis in hallux limitus patients. The immediate and long-term post-operative elevation in plantar pressure measurements beneath the second metatarsal head are the most likely aetiological factors responsible for post-operative metatarsalgia and stress fractures of the second metatarsal, that are recognised complications of this type of surgery (Boberg et al., 1987).

Although post-operative radiographs were not taken of hallux limitus subjects, the increased load to the second metatarsal is almost certainly due to the relative shortening of the first metatarsal. This shortening is due to thermal necrosis of the bone due to the use of bone saws (Jahss et al., 1985), normal absorption of bone during healing of the osteotomy (Jeremin et al., 1982), and additionally, by virtue of the nature of the particular osteotomy employed.

The third metatarsal head region showed initial significant increases in all pressure/force variables except contact time, similar to the second metatarsal head, however these initially elevated values gradually decreased by 12-months to pre-operation levels, although remaining significantly higher than the mean value for the control group. Clinically, the third metatarsal is less susceptible to post-operative metatarsalgia than the second metatarsal (Hanft, 1996), which is in keeping with the pressure measurement findings.

Pressure measurements for the fourth and fifth metatarsal regions an overall significant decrease by 24-months compared with pre-operative measurements, except for pressure-time-integral for the fourth metatarsal, which remained unchanged at a significantly higher level than the control group. The dorsiflexion range of motion of the hallux was found to improve to near normal values post-operatively and to be negatively correlated with the pre-operative peak pressure measurements of the fourth and fifth metatarsal heads. Similarly, the amount of post-operation hallucal dorsiflexion is negatively correlated with maximum force and force-time-integral of the fourth metatarsal head. In other words, limitation of dorsiflexion of the hallux due to the presence of peri-articular osteophytes and other structural factors that define the condition, may cause the foot to function in a more supinated manner, placing increased load on the lateral metatarsals. Post-operatively, the amount of available dorsiflexion of the hallux is increased, leading to a reduction in foot supination, decreasing the lateral loading of the forefoot.

8.3.2 Changes to first metatarsophalangeal joint range of motion

In this group of subjects, the Youngswick osteotomy/cheilectomy was seen to change the range of motion of the first metatarsophalangeal joint to near-normal values, with a significantly increased amount of dorsiflexion available, as measured 24-months post-operatively. The amount of post-operative plantar flexion available was minimally, although not significantly, reduced.

Simple cheilectomy, or the removal of the dorsal peri-articular osteophytes on the first metatarsal head and base of the proximal phalanx of the hallux alone, has been reported to improve the joint range of motion in mild cases (Feldman et al., 1983; and Mann et al., 1988). However, there have been no reports in the literature concerning measured changes to first metatarsophalangeal joint motion following the Youngswick procedure.

In summary, it can be demonstrated that plantar pressure measurements following the Youngswick osteotomy/cheilectomy for the treatment of hallux limitus largely effect the hallux, second, fourth and fifth metatarsal areas. The hallux experiences significant decreases in pressure, contact time and force variables that stabilise by twelve months at slightly reduced, or in the case of peak pressure, at similar to pre-operative levels. The second metatarsal area concurrently experiences significant initial increases in pressure/force variables by six months to remain at significantly higher than pre-operation levels. The most likely cause of the long-term increased pressure beneath the second metatarsal is first metatarsal shortening associated with the surgical procedure. The most plausible cause of decreased loading of the fourth and fifth metatarsal regions is an increase in the amount of available dorsiflexion of the hallux that may allow the foot to function in a less supinated position.

8.4 LIMITATIONS

The main limitation of this study was in relation to the relatively small sample size of the hallux limitus group (24 subjects), compared with the control group (36 subjects). Many of the hallux limitus patients recruited into the study pre-operatively, subsequently had simple cheilectomies or Keller arthroplasties performed at surgery, disqualifying them from further participation. Due to time constraints, recruitment of additional appropriate hallux limitus subjects was not possible.

A second limitation of the study was that although the principle researcher performed surgery on approximately 75% of the subjects in either group, employing standardised surgical techniques, a single podiatric surgeon did not perform each operation in exactly the same manner. Similarly, the post-operative management of each subject was not necessarily the same and may have varied between surgeons, which may have also influenced the results.

A final limitation was that although the radiographic technique used was standardised, the same radiographer using the same radiographic equipment did not take all of the radiographs.

CHAPTER NINE

PLANTAR PRESSURE MEASUREMENT AND RADIOGRAPHIC CHANGES FOLLOWING HALLUX VALGUS SURGERY

9.0 RATIONALE OF THE STUDY

As with hallux limitus deformity, changes to plantar pressure measurements following surgical intervention to correct hallux valgus has received little attention in the literature. At the present time, the 'modified Austin' bunionectomy is often performed to correct mild to moderate hallux valgus deformities. A review of the literature indicates that no reports have been published outlining pressure distribution changes within the foot and radiographic changes to the first metatarsophalangeal joint with respect to this operation.

9.1 METHOD

9.1.1 Subjects

Thirty-six healthy volunteers were recruited as control subjects and screened by interview to exclude any history of significant foot or lower limb pathology in the preceding twelve months and by physical examination for signs of any obvious foot or gait abnormalities. Control subjects were excluded from the study if clinical signs of pes valgus (pronated, flat foot) or pes cavus (supinated, high arched foot) or forefoot pathology such as hallux valgus or hallux limitus were noted. No attempt was made to differentiate between male and female subjects as previous studies have observed little differences in plantar pressure measurements between sexes (Bennett & Duplock, 1993; Shorten et al., 1989; Soames, 1985). With approval of the Human Research Ethics Committee of Curtin University of Technology, written consent was obtained from each subject. Refer to Appendix C.

Thirty-one subjects with hallux valgus (44 feet) were recruited from the private practices of local podiatrists. Hallux valgus subjects all had signs and symptoms of first metatarsophalangeal joint deformity of sufficient severity for them to seek advice on and subsequently undergo corrective foot surgery.

Hallux valgus was defined both radiographically when the hallux abductus angle was 20° or greater, as measured from a dorso-plantar weight-bearing x-ray, and clinically, without pain or obvious limitation of passive first metatarsophalangeal joint motion. Each hallux valgus patient underwent a modified Austin bunionectomy under general anaesthesia. Although the author performed surgery on approximately 75% of the subjects, four other podiatric surgeons conducted the remaining surgery. The practitioners were experienced with the procedure and used a standardised surgical technique. Refer to Appendix A. Subject demographics are listed in Table 9.1.

9.1.2 Equipment

An EMED SF-4 version 2.1 capacitance transducer system, with a platform dimension of 420x417 mm and sensor matrix of 360x190mm, mounted flush with the floor surface at the centre of a 10m raised walkway was used. Data were acquired with a sampling rate of 50Hz, using a platform comprised of 2736 individual sensors arranged in a matrix with a spatial resolution of $4/cm^2$.

Data for each subject recording session were written to floppy disks and later stored collectively on Iomega zip™ IBM formatted 100MB discs. Data were coded to ensure confidentiality of each subjects identity and available only to the author and the supervisors. All raw data are to be stored for seven years, as required by of the Human Research Ethics Committee of Curtin University of Technology. An IBM compatible computer was used to facilitate data organisation and analysis using appropriate software.

Table 9.1 Control and hallux valgus subject demographics

	Controls	Hallux valgus
n (subjects)	36	31
n (feet)	36	44
Gender	12m/24f	4m/27f
Mean age (yrs)	39.8 [12.0]	50.5 [11.3]
Range	23.0 - 68.0	16.0 - 74.0
Mean wt (kg)	70.1 [13.9]	74.5 [19.8]
Range	48.5 - 96.6	50.0 -141.6
Mean ht (cm)	168.7 [9.1]	168.1 [8.5]
Range	156.0-185.0	155.0-187.0
Mean BMI	24.6 [3.8]	26.2 [4.7]
Range	18.9 - 35.4	17.1 - 41.4

m = male, f = female, BMI = body mass index = $wt(kg)/ht(m)^2$,
[ ] = standard deviation

9.1.3 Procedure

Subjects were individually informed of the nature and intent of the proposed research and invited to participate. After written consent was obtained, each subject was allowed familiarisation with the testing procedure by walking over the platform at their own self-selected comfortable pace several times. Subjects were instructed not to look down at the platform to prevent targeting but to look ahead at a fixed position distant to the platform. Each control subject had data collected from the left foot with the two-step method as outlined by Myers-Rice et al. (1994). Data were collected from the feet of subject's on whom surgical correction was to be performed and for the purposes of statistical analyses, each foot thereafter was treated as a single subject.

Each person's starting position was determined such that the individual commenced walking with the opposite foot to that being tested, with the test foot making contact with the platform on the second step from the starting position. Several trials of each foot were then collected for each person, and after discarding any aberrant footfalls, three were selected for further analysis. Plantar pressure measurement data of control subjects were collected at the beginning of the trial and subsequently repeated 24 months later. Data from hallux valgus subjects were collected pre-operatively and at three, six, 12, 18 and 24 months post-operation.

9.1.4 Data and statistical analysis

The foot of each subject was divided into 10 regions or masks using the Novel-ortho software (version 08.7) 'Automask' program, to include the heel, mid-foot, first through fifth metatarsal heads, hallux, second toe and third to fifth toes. The Novel-win software (version 08.7) 'Groupmask' program was then used to group together three recorded trials of each subject into a single data file. Each data file thus formed was subsequently analysed using the Novel-win 'Groupmask Evaluation' program. Measurements of mean peak pressure [N/cm^2], pressure-time-integral [(N/cm^2)s], contact time [% roll-over-process], maximum force [% body weight] and force-time-integral [(% body weight)s], for the various masks were then generated and transferred to a Microsoft Excel 97 spreadsheet for statistical analysis using SPSS 10.0 for Windows.

During the collection period it became apparent that data from the heel, mid-foot and lesser digital masks exhibited very little variation between data collection times, while the forefoot seemed to present more dynamic changes, worthy of detailed statistical examination. Therefore, only masks within the forefoot, including the first to fifth metatarsal heads and the hallux were used in subsequent data analyses.

9.2 RESULTS

The results of plantar pressure measurements of control subjects has been presented in Chapter Eight. Refer to section 8.2.1. Changes to plantar pressure measurements of hallux valgus subjects were assessed over a 24-month period, with peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral measurements being assessed separately. Multivariate analysis of variance and within-subject contrasts were used to identify significant pressure/force changes between zero to three months, three to six months, six to 12-months, 12 to 18-months, and 18 to 24-months. Univariate contrasts were used to identify significant overall changes between zero and 24-months. In addition, a comparison of significant differences between the various plantar pressure measurements of control and hallux limitus subjects at zero and 24-months were made using independent t-tests. An alpha level of $p<0.05$ was used for all tests of significance.

Finally, since the primary objective of the modified Austin bunionectomy procedure is to correct the transverse plane position of the first metatarsal and the hallux at the first metatarsophalangeal joint, a pre- and 24-month post-operation radiographic study of each subject was performed. Bivariate correlation matrices were subsequently used to assess for relationships between radiographic and plantar pressure measurements.

9.2.1 Hallux valgus plantar pressure measurement data

To assess incremental changes to plantar pressure measurements over a 24-month period, recordings of peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral, for each hallux valgus subject were recorded pre-operatively, and repeated at three, six, 12, 18 and 24-months post-operation. Not all subjects were available for follow-up measurements for each specified period of review. The ratio of *number-of-subjects-tested* to *number-of-subjects-in-group*, for each measurement period was as follows: Pre-operation (44:44), three-months (34:44), six-months (43:44), 12-months (36:44), 18-months (30:44) and 24-months (43:44). To make complete the data for the purposes of statistical analysis, missing values were replaced with the mean score of the plantar loading variable for the period of assessment. Mean raw data with missing values are presented in Appendix K.

Multivariate analysis of variance (MANOVA) was used to test for within-subject effects of time for the various pressure/force variables for the forefoot. The independent variable was time with six test-times over a two-year period. The plantar loading variables were metatarsal heads one-to-five and the hallux. Assumption testing for univariate normality was conducted graphically, with histograms, stem-and-leaf plots, boxplots, normal probability and detrended normal plots, and each demonstrated normality of data of all pressure/force variables. Mahalanobis distance regression analysis identified multivariate outliers in peak pressure, pressure-time-integral and contact time, but not in maximum force or force-time-integral variables. Given the cell size for hallux valgus subjects was greater than 30 (44), and the outliers few in number, this violation of multivariate normality was therefore discounted and all data collected was used in the MANOVA calculations, in accordance with Coakes and Steed (1999).

Overall, for each of the dependent variables (metatarsal heads 1-5 and hallux) there were significant changes over time of all pressure/force variables; peak pressure $F_{30,1070}=5.4$, $P<0.001$; pressure-time-integral $F_{30,545}=3.6$, $P<0.001$; contact time $F_{30,545}=3.2$, $P<0.001$; maximum force $F_{30,545}=4.2$, $P<0.001$; and force-time-integral $F_{30,545}=4.9$, $p<0.001$. Maulchly's test of sphericity showed assumptions of univariate normality were violated as sphericity for the variables could not be assumed, therefore Huynh-Feldt univariate tests were used to identify the region of the forefoot exhibiting significant pressure changes. Tests of within-subject contrasts were used to reveal between which measurement period the pressure changes occurred.

9.2.1.1 Peak pressure changes over time in the hallux valgus group

During the 24-month period of observation significant changes to peak pressure measurements were found to occur beneath the first, third and fifth metatarsal heads and the hallux. Temporal changes in peak pressure of the forefoot are graphically represented in Figure 9.1. Descriptive statistics and univatiate results with contrasts for hallux valgus subjects comparing successive measurement periods to assess peak pressure changes over time, as well as the pre-operative and 24-month measurements to assess the overall changes are presented in Table 9.2. Contrasts are presented only for those variables that showed significant univariate results.

The first metatarsal initially underwent significant peak pressure reduction of approximately 33% from the pre-operation measurement and subsequently increased significantly over the following three month period to stabilise by six months. The peak pressure remained constant until 12-months at which time there was a gradual increase in peak pressure to that similar to the pre-operation state.

By comparison, peak pressure of the second metatarsal remained relatively unchanged throughout the observation period. The third metatarsal head region was also relatively constant until six months when a significant decrease in peak pressure occurred until twelve months, at which time the pressure stabilised to pre-operation levels. Similarly, the fifth metatarsal head showed a significant decrease in peak pressure between six and twelve months, that remained at significantly lower than pre-operation levels by 24-months.

The hallucal measurements of peak pressure showed a relatively large significant decrease of approximately 53% over the first three-month period that increased significantly until 12-months to stabilise at significantly lower levels than pre-operative measurements.

9.2.1.2 Overall peak pressure changes in hallux valgus group compared to control group

Control and hallux valgus mean peak pressures were compared at zero and 24 months post-operation by independent t-tests. Thirty-six subjects from the control group were compared to the same number of randomly selected hallux valgus subjects. Levene's test for equality of variance was used to test for homogeneity of variance for all pressure/force variables. Data for peak pressure of the fifth metatarsal head was seen to violate assumptions of normality, however the data was included in the analysis as the cell size for each group was greater than thirty (36). The results indicated that in the hallux valgus group, peak pressure for the fourth metatarsal head increased significantly post-operatively, while peak pressure of the hallux significantly decreased from pre-operation levels to 'normal' values by 24-months. Peak pressure for the first, second and third metatarsal heads remained significantly higher in the hallux valgus group than in the control group. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 9.3

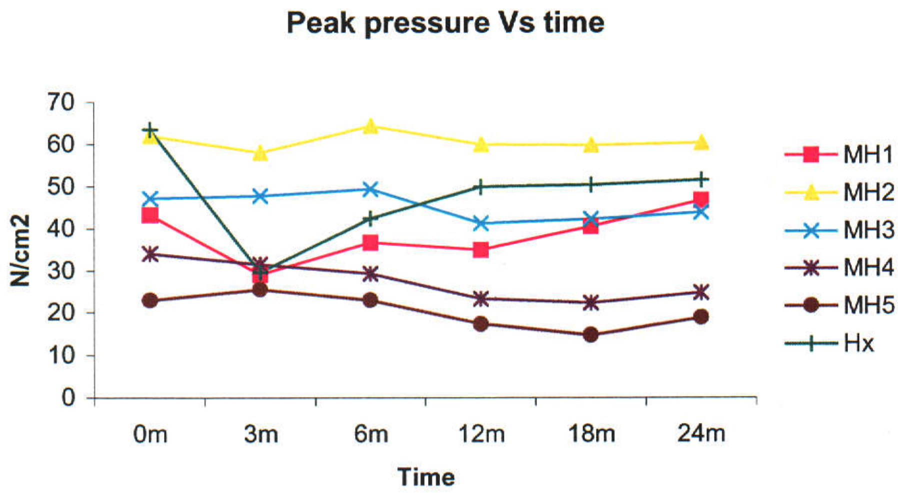
Table 9.2 Descriptive statistics (mean [SD]) and univariate results for peak pressure (N/cm^2) of hallux valgus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	43.00 [23.58]	29.05 [12.71]	36.66 [22.03]	35.04 [18.33]	40.64 [17.06]	46.84 [27.95]	8.21	4, 190	<0.001*
MH2	62.23 [24.14]	58.04 [17.28]	64.39 [24.23]	59.91 [21.72]	59.79 [19.63]	60.30 [23.31]	1.50	4, 173	0.202
MH3	47.54 [14.64]	47.94 [12.41]	49.47 [15.09]	41.39 [10.57]	42.39 [11.09]	43.94 [15.71]	5.81	4, 181	<0.001*
MH4	35.09 [42.84]	31.55 [10.00]	29.32 [15.36]	23.38 [6.89]	22.33 [7.15]	24.82 [12.13]	3.27	1, 60	0.062
MH5	23.07 [17.81]	25.54 [13.70]	22.95 [18.83]	17.34 [13.63]	14.65 [7.66]	18.73 [18.37]	5.30	3, 129	0.002*
HX	63.74 [23.47]	29.70 [12.94]	42.53 [25.40]	50.03 [26.65]	50.47 [23.17]	51.57 [29.11]	20.35	4, 164	<0.001*

Contrasts

	0 - 3m F(1,43)	p	3 - 6m F(1,43)	p	6 - 12m F(1,43)	p	12 - 18m F(1,43)	p	18 - 24m F(1,43)	p	0-24m F(1,43)	p
MH1	19.26	<0.001*	7.88	0.007*	0.38	0.542	3.46	0.070	3.07	0.087	1.49	0.228
MH3	0.04	0.836	0.47	0.495	23.11	<0.001*	0.68	0.412	1.00	0.323	2.27	0.139
MH5	0.59	0.447	0.61	0.439	4.10	0.049*	1.68	0.201	2.47	0.124	15.26	<0.001*
HX	75.56	<0.001*	14.35	<0.001*	7.79	0.008*	0.02	0.882	0.14	0.703	8.55	0.005*

MH = metatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 9.1 Mean peak pressure measurements of the forefoot in hallux valgus subjects pre- and post-operation.

9.2.1.3 Pressure-time-integral changes over time in hallux valgus group

Pressure-time-integral measurements for the third, fourth metatarsal heads and the hallux were seen to vary significantly between test periods. Temporal changes to pressure-time-integral of the forefoot are graphically represented in Figure 9.2. Descriptive statistics and univatiate results with contrasts for hallux valgus subjects comparing successive measurement periods to assess pressure-time-integral changes over time, as well as the pre-operative and 24-month measurements to assess the overall changes are presented in Table 9.4. Contrasts are presented only for those variables that showed significant univariate results.

The third and fourth metatarsal heads showed a significant decrease in pressure-time-integral between six and twelve and six and 18-months respectively. By comparison, the hallux values initially decreased by three months post-operation and then significantly increased from three to 12-months. Overall, the first metatarsal showed that a significant

Table 9.3 Results of independent t-tests comparing control and hallux valgus groups at zero and 24 months for mean peak pressure (N/cm^2)

Time	Region	Mean Controls	Mean HV Group	Mean diff. Control-HV	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	28.57 [10.88]	43.00 [23.58]	-14.13	4.42	-3.19	70	0.002*
	MH2	40.66 [15.57]	62.23 [24.14]	-20.35	4.63	-4.40	70	<0.001*
	MH3	35.15 [11.27]	47.54 [14.64]	-13.63	2.91	-4.68	70	<0.001*
	MH4	23.09 [8.26]	35.09 [42.84]	-14.83	7.93	-2.43	70	0.066
	MH5	22.19 [14.62]	23.07 [17.81]	-1.87	3.98	-1.87	70	0.640
	HX	43.80 [16.34]	63.74 [23.47]	-19.21	4.73	-0.47	70	<0.001*
24m	MH1	30.25 [9.05]	46.84 [27.95]	-16.68	4.72	-3.53	70	0.001*
	MH2	40.14 [14.46]	60.30 [23.31]	-19.42	4.65	-4.18	70	<0.001*
	MH3	33.67 [11.31]	43.94 [15.71]	-11.86	3.33	-3.57	70	0.001*
	MH4	20.35 [5.60]	24.82 [12.13]	-5.41	2.31	-2.34	70	0.022*
	MH5	17.31 [10.76]	18.73 [18.37]	-2.08	3.69	-0.56	70	0.575
	HX	43.34 [14.14]	51.57 [29.11]	-6.87	5.27	-1.30	70	0.197

HV = hallux valgus, [ ] = standard deviation, MH = metatarsal head, HX = hallux, *sig difference, α=0.05

increase in values while the fifth metatarsal and the hallux measured significantly lower values at 24-months.

9.2.1.4 Overall pressure-time-integralchanges in hallux valgus group compared to control group

Control and hallux valgus mean pressure-time-integrals were compared at zero and 24-months post-operation by independent t-tests. Thirty-six subjects from the control group were compared to the same number of randomly selected hallux valgus subjects. Levene's test for equality of variance was used to test for homogeneity of variance for all pressure/force variables, with acceptable results. The t-test results were similar to those for peak pressure. Pressure-time-integral for the first, second, third and fourth metatarsal heads were significantly higher in the hallux valgus group than in the control group, and measurements of the hallux significantly decreased from pre-operative levels to 'normal' post-operative values. Pressure-time-integral for the first, second and third metatarsal heads remained significantly higher in the hallux valgus group than in the control group. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 9.5.

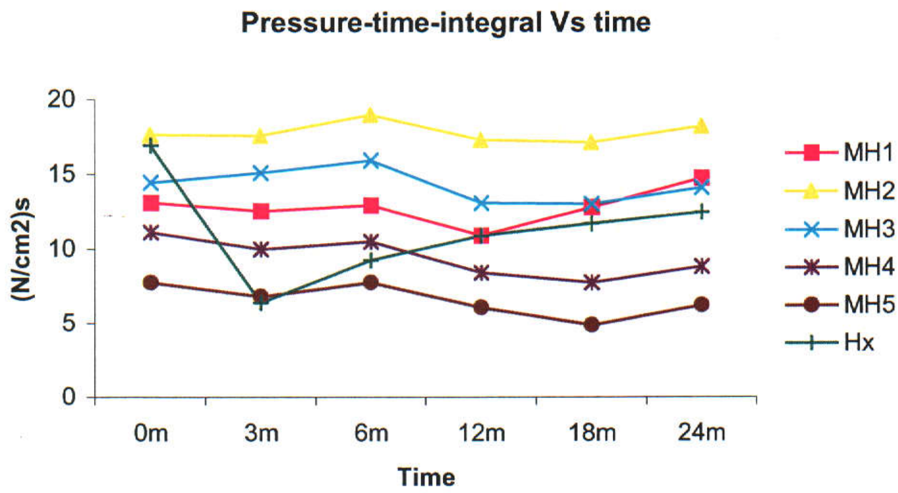
Table 9.4 Descriptive statistics (mean [SD]) and univariate results for pressure-time-integrals ([N/cm^2]s) of hallux valgus subjects 0-24 months post-operation

	Time (months) 0	3	6	12	18	24	F	df	p
MH1	13.12 [7.38]	12.56 [11.85]	12.94 [8.45]	10.93 [4.93]	12.80 [5.07]	14.75 [8.31]	1.45	2, 104	0.236
MH2	17.82 [7.58]	17.53 [4.63]	18.91 [7.57]	17.25 [6.58]	17.06 [5.50]	18.14 [7.24]	1.10	4, 167	0.355
MH3	14.69 [5.10]	15.10 [5.01]	15.94 [6.35]	13.10 [3.72]	13.05 [3.30]	14.14 [5.87]	4.85	4, 156	0.001*
MH4	11.50 [10.08]	9.98 [3.19]	10.52 [5.56]	8.40 [2.78]	7.74 [2.48]	8.84 [4.64]	4.14	2, 78	0.023*
MH5	7.87 [6.03]	6.83 [2.60]	7.77 [6.23]	6.09 [4.45]	4.89 [2.09]	6.23 [5.61]	4.64	2, 100	0.008*
HX	17.10 [8.08]	6.39 [3.33]	9.26 [6.19]	10.92 [6.34]	11.71 [5.87]	12.47 [7.67]	22.61	3, 136	<0.001*

Contrasts

	0 - 3m F(1,43)	p	3 - 6m F(1,43)	p	6 - 12m F(1,43)	p	12 - 18m F(1,43)	p	18 - 24m F(1,43)	p	0 - 24m F(1,43)	p
MH3	0.35	0.560	0.89	0.352	13.43	0.001*	0.02	0.883	2.49	0.122	32.23	<0.001*
MH4	0.95	0.335	0.44	0.509	8.59	0.005*	7.62	0.008*	3.74	0.060	3.45	0.070
MH5	1.34	0.253	1.00	0.322	3.23	0.079	3.61	0.064	2.77	0.103	22.07	<0.001*
HX	74.22	<0.001*	10.89	0.002*	4.60	0.038*	1.48	0.231	0.89	0.352	10.08	0.003*

MH = metatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 9.2 Mean pressure-time-integral measurements of the forefoot in hallux valgus subjects pre- and post-operation.

The results for peak pressure and pressure-time-integral indicate that hallux valgus feet have a medial locus of forefoot loading, seemingly pathognomic of the deformity, supporting the view that excessive foot pronation is associated with the condition and may be considered as a fundamental aetiological factor in the development of hallux valgus.

Table 9.5 Results of independent t-tests comparing control and hallux valgus groups at zero and 24 months for mean pressure-time-integral ([N/cm^2]s)

Time	Region	Mean Controls	Mean HV Group	Mean diff. Control-HV	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	9.06 [3.45]	13.12 [7.38]	-3.79	1.38	-2.75	70	0.008*
	MH2	12.23 [4.40]	17.82 [7.58]	-5.00	1.29	-3.87	70	<0.001*
	MH3	11.33 [3.43]	14.69 [5.10]	-3.65	0.97	-3.75	70	<0.001*
	MH4	8.04 [3.04]	11.50[10.58]	-4.15	1.89	-2.19	70	0.031*
	MH5	7.02 [4.54]	7.87 [6.03]	-1.12	1.31	-0.86	70	0.395
	HX	10.47 [4.42]	17.10 [8.08]	-6.64	1.44	-4.62	70	<0.001*
24m	MH1	9.48 [3.36]	14.75 [8.31]	-5.08	1.43	-3.55	70	0.001*
	MH2	11.80 [3.32]	18.14 [7.24]	-6.58	1.37	-4.82	70	<0.001*
	MH3	10.72 [2.99]	14.14 [5.87]	-4.12	1.13	-3.64	70	0.001*
	MH4	7.24 [2.29]	8.84 [4.64]	-2.01	0.90	-2.24	70	0.030*
	MH5	5.88 [3.47]	6.23 [5.61]	-0.63	1.15	-0.55	70	0.586
	HX	10.50 [4.05]	12.47 [7.67]	-1.90	1.47	-1.29	70	0.202

HV = hallux valgus, [ ] = standard deviation, MH = metatarsal head, HX = hallux, *sig difference, α=0.05

9.2.1.5 Contact time changes over time in hallux valgus group

A significant decrease in contact time was noted between six and 12-months for the third and fifth metatarsal heads, while the hallux experienced an initial significant decrease, followed by a corresponding increase in value between three and six months. Only the fifth metatarsal and hallux showed significant decreases between pre-operative and 24-month post-operation measurements. Temporal changes to contact time of the forefoot are graphically represented in Figure 9.3. Descriptive statistics and univariate results with contrasts for hallux valgus subjects comparing successive measurement periods to assess contact time changes over time, as well as the pre-and 24-month measurements to assess the overall changes are presented in Table 9.6. Contrasts are presented only for those variables that showed significant univariate results.

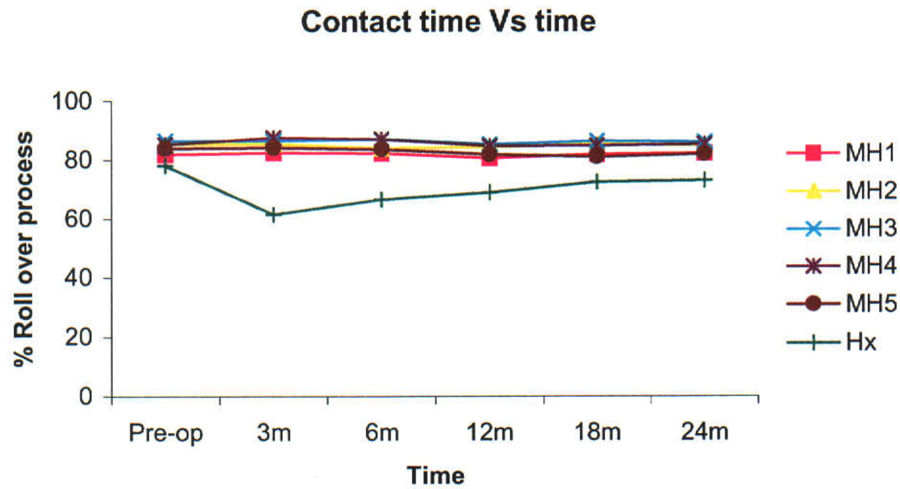
Table 9.6 Descriptive statistics (mean [SD]) and univariate results for contact time (ROP) of hallux valgus subjects 0-24 months post-operation

	Time (months)								
	0	3	6	12	18	24	F	df	p
MH1	82.04 [4.43]	82.52 [2.97]	82.24 [4.18]	80.61 [4.84]	82.02 [3.27]	82.34 [3.75]	2.16	4, 195	0.067
MH2	85.50 [3.14]	85.49 [2.88]	83.97 [11.72]	84.34 [3.81]	85.26 [2.81]	84.93 [3.58]	0.61	2, 65	0.504
MH3	86.72 [2.98]	86.68 [2.99]	87.26 [2.75]	85.50 [3.71]	86.48 [2.76]	86.11 [3.61]	2.54	5, 198	0.034*
MH4	85.48 [10.30]	87.46 [2.47]	86.93 [2.59]	84.72 [4.00]	84.93 [2.79]	85.27 [4.10]	2.37	2, 72	0.109
MH5	84.15 [3.65]	84.29 [2.67]	83.76 [3.44]	81.93 [4.12]	81.02 [4.11]	82.16 [5.47]	8.26	5, 203	<0.001*
HX	78.43 [12.96]	61.51 [14.16]	66.65 [13.50]	69.07 [11.96]	72.63 [8.24]	73.07 [13.63]	15.45	4, 168	<0.001*

Contrasts

	0 - 3m F(1,43)	p	3 - 6m F(1,43)	p	6 - 12m F(1,43)	p	12 - 18m F(1,43)	p	18 - 24m F(1,43)	p	0 - 24m F(1,43)	p
MH3	0.01	0.936	1.40	0.243	10.12	0.003*	3.71	0.061	0.48	0.491	1.73	0.196
MH5	0.07	0.793	1.58	0.216	7.54	0.009*	1.43	0.238	2.01	0.163	8.52	0.006*
HX	42.48	<0.001*	5.46	0.024*	2.60	0.114	5.40	0.025	0.06	0.810	4.19	0.047*

ROP = roll over process, MH = metatarsal head, HX = hallux, *Significant at $p<0.05$



MH = metatarsal head, Hx = hallux

Figure 9.3 Mean contact time measurements (% roll over process) of the forefoot in hallux valgus subjects pre- and post-operation.

9.2.1.6 Overall contact time changes in hallux valgus group compared to control group

Control and hallux valgus mean contact time were compared at zero and 24-months post-operation by independent t-tests. Thirty-six subjects from the control group were compared to the same number of randomly selected hallux valgus subjects. Levene's test for equality of variance was used to test for homogeneity of variance for all pressure/force variables. The t-test results indicate that contact time is significantly higher beneath the first, third and fourth metatarsal heads and lower beneath the hallux in the hallux valgus group at 24-months post-operatively compared to the control group. Contact time of the second metatarsal was significantly higher in the hallux valgus group pre- and post-operatively. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 9.7.

Table 9.7 Results of independent t-tests comparing control and hallux valgus groups at zero and 24 months for mean contact time (% ROP)

Time	Region	Mean Controls	Mean HV Group	Mean diff. Control-HV	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	79.43 [7.07]	82.04 [4.43]	-2.59	1.36	-1.91	70	0.061
	MH2	81.91 [7.43]	85.50 [3.14]	-3.84	1.35	-2.85	70	0.006*
	MH3	84.92 [6.10]	86.72 [2.98]	-2.04	1.11	-1.83	70	0.073
	MH4	83.04 [7.32]	85.48[10.30]	-2.40	2.24	-1.07	70	0.289
	MH5	79.98 [7.44]	84.15 [3.65]	-4.68	1.36	-3.45	70	0.001*
	HX	70.27 [9.78]	78.43[12.96]	-7.92	2.74	-2.89	70	0.005*
24m	MH1	81.75 [3.01]	82.34 [3.75]	-5.08	1.43	-3.55	70	0.001*
	MH2	84.08 [2.72]	84.93 [3.58]	-6.58	1.37	-4.82	70	<0.001*
	MH3	107.52[12.82]	86.11 [3.61]	-4.12	1.13	-3.64	70	0.001*
	MH4	85.19 [2.67]	85.27 [4.10]	-2.01	0.90	-2.24	70	0.030*
	MH5	81.63 [3.69]	82.16 [5.47]	-0.63	1.15	-0.55	70	0.586
	HX	74.77 [9.05]	73.07[13.63]	-1.90	1.47	-1.29	70	0.202

HV = hallux valgus, [ ] = standard deviation, MH = metatarsal head, HX = hallux, ROP = roll over process, *sig difference, α=0.05

9.2.1.7 Maximum force changes over time in hallux valgus group

All dependent variables except the fifth metatarsal head showed significant changes in maximum force over the measurement period. The first metatarsal region initially significantly decreases then increases from three to six months, then again from 12 to 18-months. The second metatarsal was seen to significantly increase initially at three months and to stabilise by 12-months to pre-operative levels. The third metatarsal head initially increased significantly by three months, then decreased significantly until 18-months to also stabilise at pre-operative levels. The fourth metatarsal showed a similar trend, stabilising by 12-months. The hallux initially showed a significant decrease at three months, to then increase until 12-months to again stabilise at pre-operation levels.

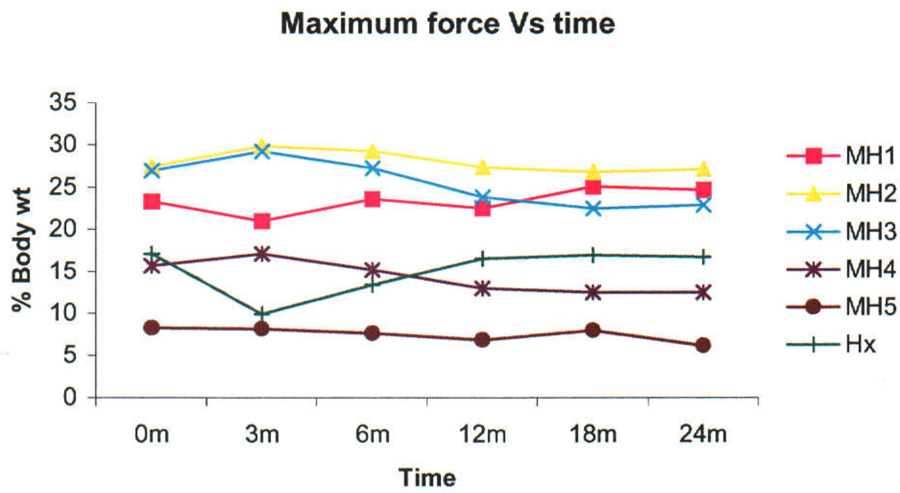
Temporal changes in maximum force of the forefoot are graphically represented in Figure 9.4. Descriptive statistics and univatiate results with contrasts for hallux valgus subjects comparing successive measurement periods to assess contact time changes over time, as well as the pre-operative and 24-month measurements to assess the overall changes are

Table 9.8 Descriptive statistics (mean [SD]) and univariate results for maximum force (% body wt) of hallux valgus subjects 0-24 months post-operation

	Time (months) 0	3	6	12	18	24	F	df	p
MH1	23.32 [8.21]	20.97 [5.92]	23.64 [6.64]	22.54 [5.95]	25.13 [5.01]	24.69 [6.94]	4.87	5, 199	<0.001*
MH2	27.36 [5.85]	29.92 [5.36]	29.27 [7.36]	27.41 [5.68]	26.80 [4.81]	27.15 [5.85	5.55	4, 175	<0.001*
MH3	26.90 [5.47]	29.26 [3.96]	27.34 [4.69]	23.86 [3.77]	22.56 [3.95]	22.98 [4.33]	38.91	4, 179	<0.001*
MH4	15.74 [3.40]	17.14 [3.32]	15.20 [4.25]	13.05 [2.74]	12.53 [3.03]	12.50 [3.41]	27.38	4, 189	<0.001*
MH5	8.28 [3.86]	8.16 [2.63]	7.59 [3.45]	6.79 [3.25]	7.99 [10.09]	6.13 [3.20]	1.49	2, 68	0.234
HX	16.99 [6.95]	9.97[4.34]	13.45 [5.77]	16.56 [5.28]	17.00 [4.69]	16.79 [6.22]	20.16	4, 164	<0.001*

Contrasts	0 - 3m F(1,43)	p	3 - 6m F(1,43)	p	6 - 12m F(1,43)	p	12 - 18m F(1,43)	p	18 - 24m F(1,43)	p	0 - 24m F(1,43)	p
MH1	4.85	0.033*	9.00	0.004*	1.65	0.206	10.45	0.002*	0.31	0.580	1.52	0.225
MH2	10.59	0.002*	0.41	0.526	3.99	0.052	1.05	0.312	0.28	0.598	0.10	0.751
MH3	10.45	0.002*	6.98	0.011*	48.05	<0.001*	10.45	0.002*	0.80	0.376	37.11	<0.001*
MH4	7.07	0.011*	8.29	0.006*	12.67	0.001*	1.27	0.266	0.01	0.945	52.53	<0.001*
HX	36.83	<0.001*	22.09	<0.001*	22.02	<0.001*	0.34	0.561	0.08	0.784	0.03	0.865

MH = metatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 9.4 Mean maximum force measurements of the forefoot in hallux valgus subjects pre- and post-operation.

presented in Table 9.8. Contrasts are presented only for those variables that showed significant univariate results.

9.2.1.8 Overall maximum force changes in hallux valgus group compared to control group

Control and hallux valgus mean maximum force were compared at zero and 24-months post-operation by independent t-tests. Thirty-six subjects from the control group were compared to the same number of randomly selected hallux valgus subjects. Levene's test for equality of variance was used to test for homogeneity of variance for all pressure/force variables. The t-test results indicate that maximum force is significantly higher beneath the third metatarsal head in the hallux valgus group pre-operatively, and decreased to 'normal' levels by 24-months post-operatively. Maximum force beneath the second and fourth metatarsal heads remained significantly higher in the hallux valgus groups post-operatively. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 9.9.

Table 9.9 Results of independent t-tests comparing control and hallux valgus groups at zero and 24 months for mean maximum force (% body wt)

Time	Region	Mean Controls	Mean HV Group	Mean diff. Control-HV	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	23.23 [6.87]	23.32 [8.21]	0.53	1.72	0.31	70	0.760
	MH2	24.97 [5.07]	27.36 [5.85]	-2.80	1.24	-2.25	70	0.028*
	MH3	23.30 [3.98]	26.90 [5.47]	-4.59	1.12	-4.09	70	<0.001*
	MH4	14.68 [4.97]	15.74 [3.40]	-1.27	1.02	-1.25	70	0.241
	MH5	7.82 [3.40]	8.28 [3.86]	-0.53	0.89	-0.60	70	0.550
	HX	21.19 [7.82]	16.99 [6.95]	4.33	1.72	-2.52	70	0.014*
24m	MH1	25.03 [6.18]	24.69 [6.94]	1.36	1.52	0.90	70	0.372
	MH2	24.86 [4.47]	27.15 [5.85]	-2.55	1.27	-2.01	70	0.048*
	MH3	22.22 [3.44]	22.98 [4.33]	-1.45	0.92	-1.58	70	0.119
	MH4	13.19 [3.12]	12.50 [3.41]	0.49	0.77	0.63	70	0.529
	MH5	6.86 [2.48]	6.13 [3.20]	0.57	0.69	0.83	70	0.412
	HX	20.42 [6.96]	16.79 [6.22]	4.08	1.57	2.59	70	0.012*

HV = hallux valgus, [ ] = standard deviation, MH = metatarsal head, HX = hallux, *sig difference, α=0.05

9.2.1.9 Force-time-integral changes over time in hallux valgus group

Significant changes of measurements of force-time-integral were found for all dependent variables except for the first metatarsal region. The second and third metatarsal heads initially showed a significant increase at three months, to significantly decrease by 12-months to pre-operative levels. The fourth metatarsal head decreased significantly between six and 18-months to reach pre-operative levels. The fifth metatarsal head appears to undergo a significant decrease in measurement between 12 and 18-months to remain at lower than pre-operative values. The hallux showed a similar trend to maximum force to decrease by three months and to then significantly increase to slightly lower than pre-operative levels by 18 and 24-months.

Temporal changes to force-time-integrals of the forefoot are graphically represented in Figure 9.4. Descriptive statistics and univatiate results with contrasts for hallux valgus subjects comparing successive measurement periods to assess contact time changes over time, as well as the pre-operative and 24-month measurements to assess for overall changes are presented in Table 9.10. Contrasts are presented only for those variables that showed significant univariate results.

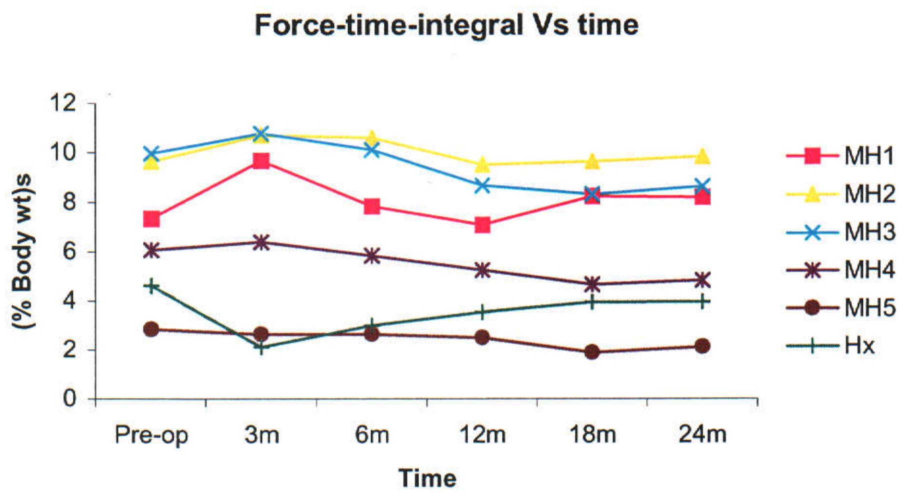
Table 9.10 Descriptive statistics (mean [SD]) and univariate results for force-time-integrals ([%body wt]s) of hallux valgus subjects 0-24 months post-operation

	Time (months) 0	3	6	12	18	24	F	df	p
MH1	7.40 [2.84]	9.69 [11.83]	7.85 [2.48]	7.10 [1.82]	8.24 [1.86]	8.22 [2.45]	1.34	1, 51	0.258
MH2	9.68 [1.91]	10.69 [1.71]	10.58 [2.46]	9.52 [2.22]	9.63 [1.88]	9.84 [2.36]	7.25	5, 210	<0.001*
MH3	9.99 [2.08]	10.78 [1.73]	10.14 [2.22]	8.70 [1.54]	8.34 [1.43]	8.65 [2.07]	27.26	4, 195	<0.001*
MH4	6.13 [1.59]	6.40 [1.29]	5.84 [1.71]	5.25 [1.97]	4.67 [1.17]	4.84 [1.52]	18.68	4, 163	<0.001*
MH5	2.88 [1.44]	2.65 [0.75]	2.65 [1.23]	2.51 [1.70]	1.90 [0.61]	2.13 [1.15]	6.74	3, 146	<0.001*
HX	4.65 [2.04]	2.13 [1.04]	3.01 [1.52]	3.56 [1.35]	3.97 [1.44]	3.97 [1.65]	24.69	4, 153	<0.001*

Contrasts

	0 - 3m F(1,43)	p	3 - 6m F(1,43)	p	6 - 12m F(1,43)	p	12 - 18m F(1,43)	p	18 - 24m F(1,43)	p	0-24m F(1,43)	p
MH2	15.04	<0.001*	0.17	0.679	21.92	<0.001*	0.28	0.601	0.48	0.494	0.27	0.604
MH3	6.12	0.017*	4.26	0.045*	33.34	<0.001*	3.89	0.055	1.84	0.181	21.64	<0.001*
MH4	1.29	0.262	3.86	0.056	6.09	0.018*	8.19	0.006*	0.84	0.364	38.14	<0.001*
MH5	1.12	0.295	0.00	0.991	0.31	0.579	6.69	0.013*	2.13	0.152	32.69	<0.001*
HX	65.57	<0.001*	19.28	<0.001*	9.82	0.003*	4.61	0.037*	0.00	0.981	4.47	0.040*

MH = metatarsal head, HX = hallux, *Significant at p<0.05



MH = metatarsal head, Hx = hallux

Figure 9.5 Mean force-time-integral measurements of the forefoot in hallux valgus subjects pre- and post-operation.

9.2.1.10 Overall maximum force changes in hallux valgus group compared to control group

Control and hallux valgus mean force-time-integrals were compared at zero and 24 months post-operatively by independent t-tests. Thirty-six subjects from the control group were compared to the same number of randomly selected hallux valgus subjects. Stem-and-leaf plots, boxplots and the Levene test for equality of variance were used to test for homogeneity of variance for all pressure/force variables. The results indicate that force-time-integral is significantly higher beneath the fourth metatarsal head pre-operatively in the hallux valgus group but reduced to similar levels at 24-months post-operatively. The second and third metatarsal heads in the hallux valgus group remained at significantly higher values post-operatively. All other areas of the forefoot retained similar values between the two groups for both measurement periods. Refer to Table 9.11.

Table 9.11 Results of independent t-tests comparing control and hallux valgus groups at zero and 24 months for mean force-time-integral ([% body wt]s)

Time	Region	Mean Controls	Mean HV Group	Mean diff. Control-HV	Std. Error diff.	t	df	Sig (2-tailed)
0m	MH1	7.46 [2.56]	7.40 [2.82]	0.30	0.63	0.48	70	0.630
	MH2	8.56 [1.69]	9.68 [1.91]	-1.02	0.40	-2.99	70	0.004*
	MH3	8.15 [1.65]	9.99 [2.08]	-2.21	0.42	-5.21	70	<0.001*
	MH4	5.33 [1.94]	6.13 [1.59]	-0.92	0.42	-2.18	70	0.032*
	MH5	2.56 [1.26]	2.88 [1.44]	-0.38	0.33	-1.14	70	0.260
	HX	4.81 [2.19]	4.65 [2.04]	0.16	0.48	0.34	70	0.735
24m	MH1	7.98 [2.06]	8.22 [2.45]	0.13	0.53	0.25	70	0.806
	MH2	8.49 [1.35]	9.84 [2.36]	-1.51	0.46	-3.24	70	0.002*
	MH3	7.94 [1.50]	8.65 [2.07]	-1.02	0.42	-2.40	70	0.019*
	MH4	4.81 [1.65]	4.84 [1.52]	-0.16	0.38	-0.42	70	0.675
	MH5	2.28 [1.04]	2.13 [1.15]	5.83E-0	20.26	0.22	70	0.826
	HX	4.60 [1.84]	3.97 [1.65]	0.69	0.40	1.72	70	0.090

HV = hallux valgus, [ ] = standard deviation, MH = metatarsal head, HX = hallux, *sig difference, α=0.05

9.2.1.11 Summary of overall changes of pressure/force variables of hallux valgus group

A summary of the overall significant plantar pressure measurement changes between the pre- and 24-month post-operation status for hallux valgus subjects is presented in Table 9.12. Decreases of most plantar loading variables to the fifth metatarsal head and hallux were found, with no apparent change to those of the first and second metatarsal heads.

9.2.2 Hallux valgus radiographic data

Essential radiographic measurements of weight-bearing pre- and post-operative x-rays were made of metatarsus primus varus, hallux abductus and first metatarsal protrusion distance. Refer to Figure 5.1 for details of these radiographic parameters.

Table 9.12 Univariate contrasts and relative changes of significant plantar pressure measurements pre- and 24 months post-operation in hallux valgus subjects

	Region	F(1,22)	*P*	% Change
Peak pressure	MH5	18.08	<0.001	19% ↓
	HX	8.55	0.005	19% ↓
Pressure-time-integral	MH1	32.23	<0.001	12% ↑
	MH5	22.07	<0.001	21% ↓
	HX	10.08	0.003	27% ↓
Contact time	MH5	8.52	0.006	2% ↓
	HX	4.19	0.047	7% ↓
Maximum force	MH3	37.11	<0.001	15% ↓
	MH4	52.53	<0.001	21% ↓
	MH5	18.04	<0.001	26% ↓
Force-time-integral	MH3	21.64	<0.001	13% ↓
	MH4	38.14	<0.001	21% ↓
	MH5	32.69	<0.001	26% ↓
	HX	4.47	0.040	15% ↓

MH = metatarsal head, HX = hallux

9.2.2.1 Correlation of hallux valgus pre-and post-operative radiographic measurements

Weight-bearing dorso-plantar radiographs were made of all hallux valgus subjects pre-operation and repeated a minimum of 24-months post-operation (mean 33.52 ± 4.72 months, range 24 - 40 months). Although the same radiographer at the same radiological practice did not take each radiograph, a standardised technique was employed. See Chapter Five for details of this technique and for examination of intra-subject rater reliability of measurement. See Appendix L for intra-rater reliability raw data. Pre- and post-operative raw radiographic data is presented in Appendix M.

Bivariate Pearson correlation coefficients were generated for pre- and post-operative radiographic measurements. Refer to Table 9.13. As might be expected, pre-operatively there was a strong positive correlation between metatarsus primus adductus and hallux abductus angles and a weaker but positive correlation between first metatarsal protrusion distance and hallux abductus angle. Post-operatively, no correlation was found between any of the measured radiographic variables. This finding is almost certainly because all

Table 9.13 Correlation of pre-and post-operative radiographic measurements in hallux valgus subjects

		Pre-operation		Post-operation	
		HA	MPD	HA	MPD
MPA	Pearson Corr.	0.728**	0.273	0.151	0.119
	Sig. (2-tailed)	<0.001	0.061	0.306	0.422
HA	Pearson Corr.		0.309*		0.191
	Sig. (2-tailed)		0.032		0.193

MPA = metatarsus primus adductus, HA = hallux abductus, MPD = 1st met. protrusion distance
Correlation significant at 0.05 level *, Correlation significant at 0.01 level **

mean post-operative radiographic measurements were less than normal reference range values.

9.2.2.2 Changes to radiographic measurements following the Austin bunionectomy

A paired t-test comparing pre- and post-operative radiographic measurements was conducted after checking that stem-and-leaf plots and boxplots of each group of measurements did not violate assumptions of normality. Descriptive statistics and the t-test results for the radiographic changes to hallux valgus subjects demonstrate significant decreases to hallux abductus angle, metatarsus primus adductus angle and first metatarsal protrusion distance measurements, and are summarised in Table 9.14.

9.2.2.3 Correlation of hallux valgus pressure/force and radiographic measurements

Bivariate Pearson correlation matrices were generated for pre- and post-operative radiographic and plantar pressure measurements. Pre-operatively, metatarsus primus adductus was weakly positively correlated with peak pressure of the first metatarsal (0.360, P=0.016). Hallux abductus angle was negatively correlated with hallucal peak pressure (-0.509, P<0.001), pressure-time-integral (-0.519, P<0.001), maximum force (-0.648, P<0.001) and force-time-integral (-0.605, P<0.001). Metatarsus primus adductus

Table 9.14 Comparison of radiographic changes in 44 hallux valgus subjects pre- and 34-months post-operation

	Pre-operation	Post-operation	Mean change	t	df	Sig.(2-tailed)
HA	27.1° [5.3]	9.5° [5.1]	-17.8°	18.67	43	<0.001
MPA	13.0° [2.9]	6.1° [1.9]	-7.1°	16.38	43	<0.001
1st MPD	2.5mm [3.2]	-2.7mm [2.3]	-5.4mm	13.60	43	<0.001

MPA = metatarsus primus adductus angle, HA = hallux abductus angle, 1st MPD = 1st metatarsal protrusion distance, [ ] standard deviation

is similarly negatively correlated with force-time-integral (-0.456, P=0.002). Post-operatively, no meaningful significant correlation was found between any plantar pressure measurements of any region of the forefoot and the post-operative x-ray parameters tested. Refer to Appendix N.

Bivariate Pearson correlation matrices were also generated to examine for correlation between pressure/force measurements and *changes* to radiographic measurements. The results showed a weak negative correlation between peak pressure of the second metatarsal head (-0.303, P=0.045) and maximum force of the second metatarsal head (-0.328, P=0.030) with change in metatarsus primus adductus. A correlation was seen between change in hallux abductus and maximum force of the hallux (-0.400, P=0.007). Refer to Appendix O.

9.2.2.4 Correlation of hallux valgus pressure/force measurements with range of motion of the hallux.

As with hallux limitus subjects, the passive range of dorsiflexion and plantarflexion of the hallux was measured with the foot in a non-weight bearing neutral position. Pre-operatively, a correlation was found for dorsiflexion of the hallux with peak pressure (0.397, P=0.008), pressure-time-integral (0.435, P=0.003), maximum force (0.473, P=0.001) and pressure-time-integral (0.658, P<0.001) with the first metatarsal head. It is likely that dorsiflexion of the hallux facilitates greater plantarflexion of the first metatarsal, increasing its load capacity. While post-operatively there was no meaningful significant correlation between any pressure variable and motion of the hallux. Refer to Appendix P.

9.2.3 Summary of the results of hallux limitus group

In summary plantar pressure measurements in the group of 44 hallux valgus subjects studied demonstrated significant changes to plantar pressure distribution within the forefoot following the modified Austin bunionectomy. The most obvious changes occurred to the hallux, demonstrating marked reductions in all pressure/force variable measurements at three months post-operation, which gradually increased until 12 to 18-months to stabilise at below normal values.

Post-operative pressure variables for the first, second and third metatarsals measured at 24-months, were largely the same as those measured pre-operatively, remaining significantly higher than control values. This finding suggests that the operation as performed, with the exception of the hallux and the fifth metatarsal, does not influence medial and central metatarsal forefoot pressure distribution. Accordingly, the modified Austin bunionectomy should not increase the likelihood of adverse long-term post-operative metatarsalgia.

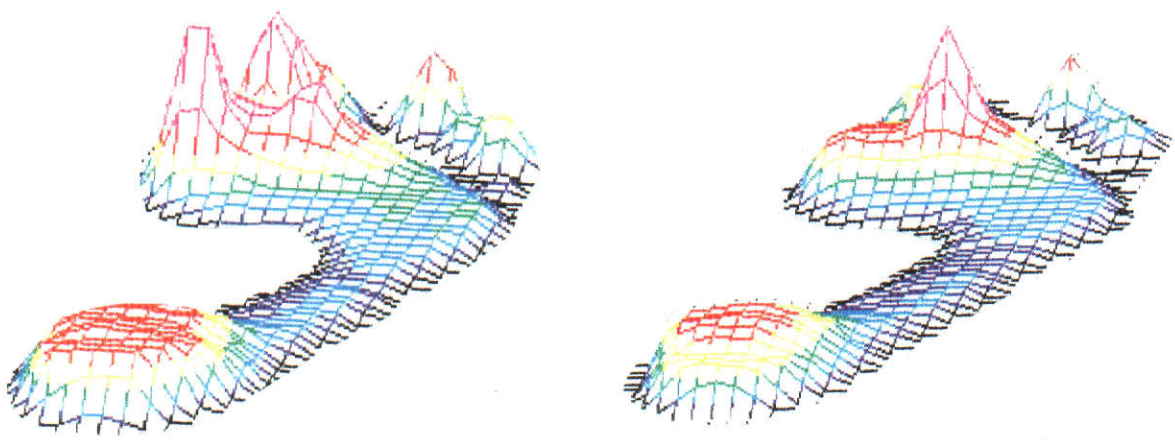
Representative two and three-dimensional EMED footprints demonstrating peak pressure distribution of a typical hallux valgus subject, pre- and 24-months post-operation, are illustrated in Figures 9.6 and 9.7.

With respect to radiographic measurements, the results indicate a positive correlation exists between hallux abductus and metatarsus adductus and between hallux abductus and first metatarsal protrusion distance. Post-operative radiographic measurements were reduced to below normal values, and post-operatively, no correlation could be found between plantar pressure distribution and range of motion of the hallux.

Pre-operation

24 months post-operation

Figure 9.6 Two-dimensional images of maximum pressure pictures of hallux valgus subject # 39



Pre-operation

24 months post-operation

Figure 9.7 Three-dimensional images of maximum pressure picture of subject # 39

In conclusion, the modified Austin bunionectomy was shown to produce significant decreases of all fundamental radiographic parameters of the first metatarsophalangeal joint of the foot in hallux valgus patients. Therefore, the hypothesis that the modified Austin bunionectomy procedure produce improved radiographic parameters to normal values is accepted.

With respect to plantar pressure distribution, surgery of the type used in this study to treat hallux valgus produced significant immediate post-operative changes to plantar pressure distribution that appear to stabilise with improved forefoot morphology over a 12 to 18-month period. Although a number of pressure/force variables of some regions of the forefoot do change from being significantly different pre-operatively to approximate normal values by 24-months post-operation, many variables at various regions become or remain significantly different post-operatively. Therefore, the hypothesis that plantar pressure measurements of feet with hallux valgus change to approximate normal values following corrective surgery of the type performed is rejected.

9.3 DISCUSSION

Fourty-four subjects with symptomatic hallux valgus deformities were assessed pre-operatively and repeated measures of plantar pressure measurements were made over a 24-month period following surgery. Essential weight-bearing dorso-plantar radiographic parameters to the hallux valgus group were also recorded pre-operation and again at 24 months post-operation.

With respect to subject demographics, the control group represented a more homogenous gender balance, while a female bias was seen in the hallux valgus group. The mean age and body mass index of the control group was less than the surgery group, however these factors were not found to correlate with any pressure variable tested in the control group. Therefore, given the relatively modest differences involved and the absence of any demonstrable effect in the control group, age and gender differences are unlikely to have adversely effected pressure measurements in the test group.

9.3.1 Plantar pressure measurement changes to the hallux valgus group

There appears to be no studies published investigating the effects of the modified Austin bunionectomy procedure on plantar pressure measurement within the forefoot using the EMED-SF system. Indeed, there have been very few published reports describing the effects of hallux valgus procedures on plantar pressure distribution within the foot and those that have been published largely concentrated on peak pressure changes only (see Table 2.1).

Plantar pressure measurement of the hallux following surgery demonstrated significant initial decreases in all pressure/force variables tested at three months, which all then rose significantly to stabilise by 12 to 18-months, significantly lower than pre-operation measurements and approximating normal values. These findings are similar to lower post-operation pressures of the hallux found by Resch and Stenstrom (1995) and Hutton and Dhanedron (1981). Only maximum force recorded similar pre- and twenty-four months post-operation measurements. Clinically, symptomatic medial-plantar callous of the hallux is a common finding in hallux valgus feet (Ruch et at., 1987; Palladino, 1991), that often disappears post-operatively and is in keeping with the findings of reduced peak pressure and pressure-time-integral of the hallux.

Peak pressure of the first metatarsal is similar to the hallux in that a significant decrease to three months is followed by a significant increase to six months, followed by a continued gradual increase to eighteen months to remain at statistically similar pre-operation levels, significantly higher than the control group. Pressure-time-integral gradually decreases until 12-months and then returned to levels significantly higher than pre-operation. Contact time for the first metatarsal remained relatively constant throughout the measurement period. Maximum force follows a similar pattern to peak pressure except that it reached pre-operation values a little later at 18-months, while force-time-integral shows a significant initial increase at three months followed by a significant decrease at six months, to stabilise at a significantly higher than pre-operation levels.

Pressure changes to the hallux and first metatarsal head areas are most noticeable within the first twelve months following surgery and can be explained in terms of the post-operation reparative process. The modified Austin bunionectomy involves an osteotomy of the head of the first metatarsal that takes approximately two months to heal. Although weight-bearing on the foot is permitted immediately, during this time the patient will tend to guard the area of operation and a more natural style of walking develops progressively as the foot recovers and the level of discomfort related to weight-bearing decreases.

Pressure variables for second metatarsal head remained relatively constant throughout the test period, with only maximum force and force-time-integral values showing an initial significant increase at three months, followed by a reduction to pre-operation measurements by six to 12-months. Peak pressure, pressure-time-integral and contact time measurements of the third metatarsal showed a gradual but not significant increase immediately post-operation, which decreases significantly over the 6 to 12-month period to pre-operation levels. These findings are similar to that of Yamamoto (1996), who found peak pressure beneath the second and third metatarsals increased initially following surgery and then return to pre-operative levels 26-months post-operation.

Maximum force and force-time-integral values followed a similar trend to stabilise by eighteen months with significantly lower levels compared with the pre-operation measurements. In general the findings relating to the second and third metatarsals are in keeping with the recognised complication of metatarsalgia of the central forefoot that sometimes follows bunion surgery and is thought to be related to first metatarsal shortening (Boberg et al., 1987; Hanft, 1996). In the hallux valgus subjects studied, the mean post-operation first metatarsal shortening was 5.2mm, although no statistically significant correlation could be found between first metatarsal protrusion distance and any pressure variable for any region of the forefoot.

Plantar pressure measurements to the fourth metatarsal head showed no overall significant change in peak pressure, pressure-time-integral or contact time between pre- and 24-months post-operation. Only maximum force and force-time-integral demonstrate overall significant reduction over this period. All pressure variables for the fifth metatarsal head however, showed significant overall reduction in values over the 24-months. These findings are contrary to earlier studies of Stokes et al., (1979) and Hutton and Dhanedron (1981), who found increased peak pressures beneath the fourth and fifth metatarsal heads, following the Keller arthroplasty procedure.

9.3.2 Changes to radiographic measurements following hallux valgus surgery

With respect to radiographic changes following surgery, significant reductions in metatarsus primus adductus, hallux abductus and first metatarsal protrusion distance were seen. The approximate decrease in hallux abductus angle was 18°, in metatarsus primus adductus 7°, and first metatarsal protrusion distance of 5mm. These findings were similar to previous studies of the Austin bunionectomy (Duke, 1986; Seiberg et al., 1994; Kalish & Spector, 1994; Bryant & Singer, 1998). Theses findings suggest that the surgical procedures were carried out in a relatively standardised manner, producing radiographic measurements consistent with accepted post-operative normal values.

In summary, the modified Austin bunionectomy for the correction of hallux valgus deformity induced significant initial reductions in all pressure/force variables to the hallux and most variables except contact time and force-time-integral to the first metatarsal head. The surgery results in significant long-term reductions in all hallucal pressure variables compared to normal values except for maximum force. The first and second metatarsal heads remained remarkably stable overall, with only significant increases to pressure-time-integral and force-time-integral for the first metatarsal, and little if any significant change to any variable tested for the second metatarsal head, either between test periods or overall. Both first and second metatarsal values remained significantly higher than the control measurements. Pressure variables and contact time of the central third and fourth metatarsals showed no significant overall changes, while significant decreases in force variables for this area were noted. Similarly, significant long-term reductions in all pressure/force variables were found for the fifth metatarsal head.

9.4 LIMITATIONS

The main limitation of the study was that although the principle researcher performed surgery on approximately 75% of the subjects in either group, employing standardised surgical techniques, a single podiatric surgeon did not perform each operation in exactly the same manner. Similarly, the post-operative management of each subject was not necessarily the same and may have varied between surgeons, which may have also influenced the results.

A second limitation was that although the radiographic technique used was standardised, the same radiographer using the same radiographic equipment did not take all of the radiographs.

CHAPTER TEN

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

10.1 SUMMARY

Hallux valgus and hallux limitus are common foot deformities that are usually a result of structural abnormalities leading to forefoot malfunction. The measurement of dynamic plantar pressure distribution during gait may assist the clinician in further understanding the pathomechanics of foot deformity and to monitor the effects of surgical intervention. As plantar pressure distribution changes within the foot following surgical correction of hallux valgus and hallux limitus have received only scant attention in the podiatric and orthopaedic literature, a series of studies were developed to investigate this subject.

10.1.1 Study One (Chapter Three): A comparison of the reliability of plantar pressure measurements using the two-step and mid-gait methods of data collection.

The reliability of plantar pressure measurements at seven selected sites of the foot in ten normal subjects, using the midgait and two-step data collection techniques was compared. Differences in contact area, contact time, maximum force and peak pressure between the two data collection methods were compared using data from 30 subjects. The purpose of the study was to determine if the more two-step method of data collection was as reliable as the traditional mid-gait technique. With few exceptions, the reliability of most measurement variables at most sites of the foot was found to be good to excellent, with the two-step method yielding higher ICC values overall. With the exception of contact time, no statistical difference was found between measurements obtained from the two data collection techniques for most sites of the foot.

The results indicate that for the subjects tested, the two-step method produced data at least as reliable and accurate as the more traditional midgait technique. The authors therefore suggest that the two-step technique may be a viable alternative to the midgait technique, as this method is relatively simple for subjects to perform and is less time consuming for the researcher. Another advantage is that the area required for a suitable walkway is considerably less for the two-step method, which may be important in the clinical setting where space is often at a premium.

10.1.2 Study Two (Chapter Four): Normal values of plantar pressure measurements determined using the EMED-SF system.

Selected plantar pressure measurements including peak pressure, average pressure and pressure-time-integrals of 10 regions of 30 healthy subjects, using the two-step technique and an EMED SF platform system, were recorded and descriptive statistics generated from the data. Normal reference range values of these variables derived from the EMED-SF system had not previously been reported in the literature. Peak force values were in broad agreement with previously reported measurements, and showed maximum values in the heel, second and third metatarsal heads and hallux.

Mean pressures demonstrate similar trends to peak pressure at all regions tested. Plantar pressure measurements were seen to vary least in the heel, second and third metatarsal heads, and vary most in the midfoot, fifth metatarsal head and lesser digits.

Normal values of pressure-time-integrals for the group of subjects tested are presented, which should prove to be of value in clinical practice for the purposes of screening and post-operative outcomes research.

10.1.3 Study Three (Chapter Five): A comparison of radiographic measurements in normal, hallux valgus and hallux limitus feet.

Selected measurement parameters of weight bearing dorso-plantar and lateral foot radiographs of 30-control, 30-hallux valgus and 30-hallux limitus subjects, were analysed for significant differences. A comparison of this nature had not previously been reported in the literature.

With respect to dorso-plantar radiographic measurements, hallux valgus was significantly associated with an increase in first metatarsal protrusion distance, which is most likely precursory to the development of the other significant findings, metatarsus primus adductus and increased metatarsal width. By contrast, hallux limitus was associated with increased hallux interphalangeal angles compared with the hallux valgus group. With respect to lateral radiographic measurements, no significant relationships were found for any of the three groups.

These findings suggest that a relatively long first metatarsal is implicated in the development of hallux valgus, and that an increased hallux interphalangeal angle may be predictive of the development of hallux limitus. From a clinical perspective, it may be prudent to consider these abnormalities when screening patients for hallux valgus and hallux limitus, or when surgical correction of these deformities is being considered.

10.1.3 Study Four (Chapter Six): Plantar pressure distribution in normal, hallux valgus and hallux limitus feet.

Selected dynamic plantar pressure measurements of 30 control, 30 hallux valgus and 30 hallux limitus subjects, using an EMED-SF system and a two-step method of data collection, were analysed for significant differences, with a one-way analysis of variance being performed with a level of significance of $p<0.05$. A comparison of plantar pressure distribution between normal, hallux valgus and hallux limitus feet had not previously been reported in the literature.

Hallux valgus feet demonstrated significant medial localisation of peak and mean pressures, suggesting foot pronation may be an important factor in the development of this condition. While hallux limitus feet showed a significant locus in mean pressure under the hallux, third and fourth metatarsal heads and lesser toes, indicating a degree of lateral bias forefoot load. From this work, it would appear that the functional pathomechanics of hallux valgus and hallux limitus feet are considerably different. These findings may be of value in assessing and monitoring patients with forefoot pathology or screening individuals at risk of developing hallux valgus or limitus so that appropriate advice or interventative treatment may be considered.

10.14 Study Five (Chapter Seven): Radiographic measurements and plantar pressure distribution in normal, hallux valgus and hallux limitus feet.

The relationship between static osseous radiographic foot measurements and mean peak pressure recordings of ten selected regions of the foot in 30 normal subjects and in 30 subjects with hallux valgus or hallux limitus was investigated. No studies of this nature comparing normal with hallux valgus and hallux limitus feet had previously been published.

The results of this study suggest that dynamic peak pressure distribution beneath the sole of the foot is unrelated to the static weight-bearing radiographic parameters tested, in normal, asymptomatic subjects and those with hallux valgus or hallux limitus. Furthermore, that weight-bearing radiographic measurements tested may not be used to predict plantar peak pressure distribution. Other intrinsic or extrinsic biomechanical, physical and physiological factors, which may have an influence on plantar pressure distribution within the foot, require further investigation.

10.1.5 Study Six (Chapter Eight): Plantar pressure measurement and range of motion changes following hallux limitus surgery.

Plantar pressure measurements of thirty six control subjects (36 feet) and seventeen hallux limitus subjects (23 feet), were recorded over a twenty four month period, using an EMED-SF system and the two-step method of data collection. All patients underwent a Youngswick osteotomy/cheilectomy procedure. Surgery subjects had pressure measurements taken pre-operatively, then at three, six, 12, 18 and 24-months post-operation, while control subjects were measured at zero and 24-months. Passive range of motion of the first metatarsophalangeal joint was recorded of hallux limitus subjects pre-operatively and repeated 24-months post-operatively.

The study presents plantar pressure measurement findings of subjects undergoing a specific surgical procedure that has not previously been reported in the literature - temporal changes to plantar pressure measurements - peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral of the forefoot, including each metatarsal head and the hallux. Similarly, range of motion changes to the first metatarsophalangeal joint following the Youngswick procedure has not previously been reported in the literature.

Hallux limitus feet experienced considerable significant plantar pressure changes in the initial three months post-operation that gradually changed over twelve to eighteen months, which for most areas of the forefoot returned to pre-operative, rather than normal values.

Pressure variables of the hallux significantly decreased following surgery to stabilise at significantly lower levels than pre-operation, except for peak pressure, which was unchanged. The second metatarsal head experienced a concurrent significant initial increase in pressure/force variables that stabilisd by six months to be significantly higher than pre-operative values. This observation is probably a result of surgical shortening of the first metatarsal, which is one of the primary objectives of the operation. In comparison the fourth and fifth metatarsal head areas underwent an overall decrease in most pressure/force variables, which are negatively correlated with increased post-operative dorsiflexion of the hallux, which may have allowed the foot to function in a less supinated manner.

Pre- and 24-month post-operation measurements of passive range of motion of the hallux at the first metatarsophalangeal joint demonstrated significant improvement due to increased available dorsiflexion to approximate a relatively normal range of motion.

10.1.6 Study Seven (Chapter Nine): Plantar pressure measurement and radiographic changes following hallux valgus surgery.

Plantar pressure measurements of 36 control subjects (36 feet) and 31 hallux limitus subjects (44 feet), were recorded over a twenty four month period, using an EMED-SF system and the two-step method of data collection. Hallux valgus patients underwent a modified Austin bunionectomy procedure. Pressure measurements were taken pre-operatively, then at three, six, 12, 18 and 24-months post-operation, while control subjects were measured at zero and 24-months. Weight-bearing radiographs of each hallux valgus subject were taken pre-operatively and repeated after a mean of 33.5-months following surgery.

The plantar pressure measurement changes following the modified Austin bunionectomy presents findings which have not previously been reported in the literature - temporal changes to plantar pressure measurements - peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral of the forefoot, including each metatarsal head and the hallux.

Hallux valgus feet experienced considerable significant plantar pressure changes in the initial three months post-operation that gradually changed over twelve to eighteen months, which for most pressure/force variables at most regions of the forefoot returned to pre-operative, rather than to normal values.

Significant initial decreases in most plantar pressure variables for the hallux and to the first metatarsal head area were seen. The surgery caused long-term significant reductions in pressure variables to the hallux to return to normal values, except for maximum force, which remained similar to pre-operation values. Peak pressure, maximum force and contact time of the first metatarsal head gradually increased to pre-operation levels by 12 to 18- months, while most values for the second metatarsal head remain relatively constant throughout the test period. Pressure variables and contact time for the third and fourth metatarsal heads showed no significant changes overall, while significant long-term decreases in force variable parameters for the central forefoot were seen. Finally, significant reductions in most plantar pressure variables for the fifth metatarsal head were found.

Significantly improved post-operative radiographic changes following the modified Austin bunionectomy were similar to previously reported values, indicating that the operation was performed in a manner producing favorable post-operative structural alignment. No meaningful significant correlations were found between radiographic measurements studied and plantar pressure/force distribution of the forefoot.

10.2 CONCLUSIONS

In conclusion, a series of seven independent but related studies examined issues related to dynamic plantar pressure distribution in normal, hallux valgus and hallux limitus feet and pressure changes associated with corrective foot surgery over a two-year period.

Plantar pressure data from all subjects were collected with a commercially available EMED-SF system using the two-step method of data collection. The two-step method was compared for consistency of measurement with the traditional midgait technique and found to provide pressure data at least as reliable as for the midgait method. This finding suggests that plantar pressure measurements recorded on similar equipment in the clinical setting, where space is often at a premium, may be considered to be a reliable form of objective plantar podiatric assessment.

To assist the clinician and researcher to use plantar pressure measurements as a diagnostic tool or to monitor changes to pressure distribution over time or after therapeutic intervention, normal reference range values for ten regions of the foot were calculated, including the pressure variables of peak pressure, mean pressure, and pressure-time-integral. The results show that peak pressure and mean pressure recordings follow very similar trends, suggesting that either variable may be used to assess pressure distribution within the foot.

Radiographic and plantar pressure measurements of normal, hallux limitus and hallux valgus feet were compared for differences. The results indicate that hallux limitus and hallux valgus feet show significant differences in both radiographic structure and planar pressure distribution. Radiographically, hallux limitus feet have greater hallux abductus interphalangeal angles compared to normal and hallux valgus feet. Hallux limitus feet appear to function in a more supinated manner with increased loading of the hallux, third metatarsal head area and lesser toes.

On the other hand, abnormally long first metatarsals were noted in hallux valgus feet and that is suggested as a structural aetiological factor predisposing the development of metatarsus primus adductus and hallux abductus – the hallmarks of hallux valgus deformity. Peak pressures in hallux valgus feet tend to be more medially focused beneath the first, second and third metatarsal heads, supporting excessive pronation of the foot as a functional aetiological factor in the development of the condition.

These findings may prove to be useful as screening tools for the early identification of the determinant factors of hallux limitus and hallux valgus for patient's with minimal objective or subjective symptoms.

Pre- and post-operation plantar pressure measurements of the forefoot in hallux limitus and hallux valgus patients were performed to identify changes to peak pressure, pressure-time-integral, contact time, maximum force and force-time-integral over a 24-month period. The research demonstrated that surgical intervention in both groups caused significant change to plantar pressure measurements, reflecting the characteristics of the individual conditions, the surgical procedures involved in their management and the nature of the healing process. The Youngswick osteotomy/cheilectomy as performed on this series of subjects, demonstrated a normal range of motion at 24-months post-operation. The first metatarsal head plantar pressure measurements remained relatively stable throughout the period of observation, suggesting that while the osteotomy 'shortens and plantar-flexes' the first metatarsal, the net load-bearing function of the first metatarsal is preserved. Other important changes to plantar pressure distribution include significant reductions in most variables of the hallux and lateral metatarsal heads and a concomitant significant increase in variables associated with the second metatarsal head.

The modified Austin bunionectomy, a popular contemporary procedure for the surgical treatment of hallux valgus, produced long-term post-operation radiographic measurements consistent with accepted values. Plantar pressure changes show significant long-term reductions of most variables of the hallux to normal values. The first metatarsal pressure measurements underwent initial decreases to increase and stabilise by twelve months, while the second metatarsal remained stable throughout the observation period, both at significantly higher than control levels. The third and fourth metatarsals show little variation of pressure variables over time, with the fifth demonstrating significant reductions in all measured variables.

The research indicates that both immediate and longer-term functional changes occur to the foot, as measured by plantar pressure distribution, follow surgical intervention of the type used to correct hallux limitus and hallux valgus. Indeed, post-surgical foot function continues to change over a twelve to eighteen month period of time before stabilising, indicating that the actual recuperative process continues far beyond the 'healed' clinical appearance of the foot. A finding that behooves foot surgeons to advise their patients accordingly and to continue to monitor a patient's progress well beyond the standard three-month period.

10.3 RECOMMENDATIONS

The findings of the series of studies within this thesis highlights a number of areas that could be examined in the future:

A. As only a small number of significant radiographic differences were identified between the sample of thirty normal, hallux valgus and hallux limitus feet, it would be valuable to repeat the study with an expanded number of subjects.

B. A comparison of pre-and post-operation (mean 33.5-months) radiographic measurements following the modified Austin bunionectomy for the treatment of hallux valgus, suggested the operation produced acceptable mid-term results. However, a follow-up study at five years post-operation would help to determine the long-term objective results of the operation.

C. This study identified normal reference range values of peak pressure, mean pressure and pressure-time-integral in a sample of thirty subjects. A similar study with an expanded sample size of subjects, with age group categorisation, to include other pressure variables such as contact time, maximum force and force-time-integral would be very useful.

D. This study identified certain significant differences of dynamic plantar pressure distribution between normal feet and those with the symptomatic structural abnormalities of hallux valgus and hallux limitus feet. It would be valuable to compare plantar pressure distribution between normal feet and those with fundamental structural abnormalities such as pes valgus (pronated or flat) feet and pes cavus (supinated or high-arched) feet. Similarly, a comparison of normal asymptomatic feet with subjects suffering with chronic symptomatic conditions such as Morton's neuroma (nerve entrapment syndrome of the forefoot) and plantar fasciitis (heel pain) would be very useful. Such studies could potentially increase our understanding of the pathomechanics of these foot conditions and further investigate the value of plantar pressure measurement as a clinical diagnostic tool.

E. The significant increased loading of the second metatarsal following the Youngswick procedure for the correction of hallux limitus deserves further long-term examination. A combined longitudinal plantar pressure measurement and clinical subjective study would be useful to ascertain if the operation causes any long-term adverse sequela.

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APPENDIX A

DESCRIPTION OF MODIFIED AUSTIN BUNIONECTOMY

The patient is brought into the operating theatre and placed on the operating table in a supine position. General or sedating anesthesia may or may not then be administered by an anaesthetist. Local anaesthesia of 10ml of 0.5% Marcaine with 1:200,000 adrenaline is then injected in a Mayo block fashion around the first metatarsophalangeal (mpj) area. A small amount of local anaesthetic is also infiltrated along the area to be incised to reduce the amount of capillary bleeding during the initial phases of the surgery.

After appropriate prepping and draping of the foot, attention is then directed to the dorso-medial aspect of the first mpj area, where a linear incision, 5-7cm in length, is made medial to the tendon of extensor hallucis longus. The incision is deepened through the skin and superficial fascia and any vessels transected are identified and electrocoagulated or ligated with 4-0 Vicryl as necessary.

Separation of the superficial and deep fascia to the medial aspect of the first mpj is then performed using a combination of sharp and blunt dissection. Attention is then directed towards the first/second intermetatarsal space where the separation of the superficial and deep fascia is achieved in a similar fashion. Dissection is carried down to the level of the deep transverse intermetatarsal ligament, which is transected using Metzembaum scissors to expose the distal insertion of the adductor hallucis tendon. The adductor tendon is then clamped with mosquito forceps and with a scalpel, dissected free from its insertion into the base of the proximal phalanx and lateral sesamoid, retracted from the wound and approximately 1cm of the tendon resected distally. The lateral sesamoidal ligament is identified and sectioned. The sesamoids are then seen to be relatively mobile underneath the first metatarsal head.

Attention is then directed to the dorso-medial aspect of the first mpj, where a dorsal longitudinal incision is made through the joint capsule extending from the neck of the first metatarsal and extending on to the base of the proximal phalanx. The capsulotomy is fashioned into a 'T' shape by making a vertical medial incision into the capsule just distal to the medial epicondyle of the first metatarsal head. The periosteum and first mpj capsule are freed and reflected to allow visualisation of the metatarsal head and to dis-articulate the first mpj.

Using a sagittal power saw, the dorsal and medial osteophytic bone from the first metatarsal head is removed, taking care to leave the sagittal groove intact. A 1.1mm K-wire is then inserted into the medial aspect of the metatarsal head as an osteotomy guide, defining the apex of the osteotomy cuts to create slight shortening and slight plantar flexion of the metatarsal head, once displaced laterally. A sagittal saw is used to cut the dorsal and plantar arms of the Austin osteotomy, creating an angle of approximately 60°. The guide wire is then removed and the distal capital fragment thus formed, is displaced laterally no more than 50% of the width of the metatarsal and impacted with firm digital pressure onto the neck of the first metatarsal.

The range of motion of the first mpj and position of the hallux is checked before fixating the osteotomy with a single 1.4mm K-wire, inserted from proximal, medial, dorsal, to distal, lateral, plantar from the first metatarsal neck into the metatarsal head. The K-wire is seen to penetrate the articular cartilage of the first metatarsal head at the level if the intersesamoidal crista and is retracted back into subcondral bone. The osteotomy is checked for stability and the wire is bent, cut and pressed flat against the shaft of the first metatarsal shaft. The resulting medial prominence of the first metatarsal shaft is removed using a sagittal saw and any remaining irregular osseous surface around the dorso-medial aspect of the first mpj is smoothed with a power burr. The wound is then copiously flushed with sterile saline.

A second vertical capsular incision, parallel to the first incision, is made to resect the redundant medial capsule. Capsulorrhaphy is performed using 3-0 Vicryl dorsally and 2-0 Vicryl medially, with the hallux held in a rectus position. A simple subcuticular running suture of 4-0 polypropylene is used to close the skin. A further injection of 4ml 0.5%

plain Marcaine with 4mg dexamethasone sodium phosphate is then injected into and around the operative area.

Betadine™ antiseptic solution is painted over the surgical site, which is allowed to dry before Steristrips™ are applied over the incision. The foot is then dressed with sterile gauze and crepe bandage with the hallux held in an anatomically correct position.

A post-operative shoe is applied to the patient's foot. Instructions to the nursing staff include keeping the patient's foot elevated, observance of the circulatory status of the foot at regular intervals, the application of periodic ice packs to the dorsum of the foot and allowing ambulation with assistance, once fully recovered from the anaesthetic. Appropriate post-operative radiographs to check alignment of the osteotomy are ordered.

APPENDIX B

DESCRIPTION OF YOUNGSWICK OSTEOTOMY/CHEILECTOMY PROCEDURE

The patient is brought into the operating theatre and placed on the operating table in a supine position. General or sedating anaesthesia may or may not then be administered by an anaesthetist. Local anaesthesia of 10ml of 0.5% Marcaine with 1:200,000 adrenaline is then injected in a Mayo block fashion around the first metatarsophalangeal (mpj) area. A small amount of local anaesthetic is also infiltrated along the area to be incised to reduce the amount of capillary bleeding during the initial phases of the surgery.

After appropriate prepping and draping of the foot, attention is then directed to the dorso-medial aspect of the first mpj area, where a linear incision, 5-7cm in length, is made medial to the tendon of extensor hallucis longus. The incision is deepened through the skin and superficial fascia and any vessels transected are identified and electrocoagulated or ligated with 4-0 Vicryl as necessary.

Separation of the superficial and deep fascia to the medial aspect of the first mpj is then performed using a combination of sharp and blunt dissection. Attention is then directed towards the first/second intermetatarsal space where the separation of the superficial and deep fascia is achieved in a similar fashion.

Attention is then directed to the dorso-medial aspect of the first mpj, where a dorsal longitudinal incision is made through the joint capsule extending from the neck of the first metatarsal and extending on to the base of the proximal phalanx. The capsulotomy is fashioned into a 'T' shape by making a short vertical medial incision into the capsule just distal to the medial epicondyle of the first metatarsal head. The periosteum and first mpj capsule are freed and reflected to allow visualisation of the metatarsal head and to dis-articulate the first mpj. Visual inspection of the head of the first metatarsal and base of the proximal phalanx of the hallux is then made to appreciate the extent of degenerative joint disease present.

Using a sagittal power saw, the dorsal and medial osteophytic bone from the first metatarsal head is removed, taking care to leave the sagittal groove intact. A 1.1mm K-wire is then inserted into the medial aspect of the metatarsal head as an osteotomy guide, defining the apex of the osteotomy cuts to be at right angles to the mid-line of the foot and parallel to the plantar aspect of the foot. A sagittal saw is used to cut the dorsal and plantar arms of the Austin osteotomy, creating an angle of approximately 90°. A second dorsal osteotomy cut is then made 2-4mm proximal and parallel to the first cut. The dorsal section of metatarsal thus formed is removed from the wound.

The guide wire is then removed and the distal capital fragment is impacted with firm digital pressure onto the neck of the first metatarsal. The range of motion of the first mpj and position of the hallux is then checked, with further dorsal bone being removed from the second osteotomy cut should the passive range of dorsiflexion of the hallux be less than normal. Fixation of the osteotomy is accomplished with either a single 1.4mm K-wire, inserted from proximal, medial, dorsal, to distal, lateral, plantar from the first metatarsal neck into the metatarsal head, or by two crossed 1.1mm K-wires. The K-wire is seen to penetrate the articular cartilage of the first metatarsal and retracted back into subcondral bone. The osteotomy is checked for stability and the wire is bent, cut and pressed flat against the shaft of the first metatarsal shaft. Any remaining irregular osseous surface around the dorso-medial aspect of the first metatarsal head and dorsal surface of the base of the proximal phalanx is smoothed with a power burr. The wound is then copiously flushed with sterile saline.

Capsulorrhaphy is performed using 3-0 Vicryl dorsally medially, with the hallux held in a rectus position. A simple subcuticular running suture of 4-0 polypropylene is used to close the skin. A further injection of 4ml 0.5% plain Marcaine with 4mg dexamethasone sodium phosphate is then injected into and around the operative area.

Betadine™ antiseptic solution is painted over the surgical site, which is allowed to dry before Steristrips™ are applied over the incision. The foot is then dressed with sterile gauze and crepe bandage with the hallux held in an anatomically correct position.

A post-operative shoe is applied to the patient's foot. Instructions to the nursing staff include keeping the patient's foot elevated, observance of the circulatory status of the foot at regular intervals, the application of periodic ice packs to the dorsum of the foot and allowing ambulation with assistance, once fully recovered from the anaesthetic. Appropriate post-operative radiographs to check alignment of the osteotomy are ordered. The patient is requested to perform active range of motion exercises of the first mpj several times a day commencing immediately post-operatively.

APPENDIX C

CONSENT FORM USED FOR SURGICAL SUBJECTS

Title of project	Plantar pressure distribution changes with hallux valgus and hallux limitus surgery.
Investigator	Alan R. Bryant BSc(Pod), MSc.
Supervisors	Dr Paul Tinley, Head, Department of Podiatry. Associate Professor Kevin Singer, School of Physiotherapy.

Purpose of research

I have been informed that this study will investigate the differences between hallux valgus and hallux limitus and test the effectiveness of the surgical treatment of these conditions. This study should help podiatrists use plantar pressure measurement technology to evaluate forefoot deformities and the role of this technology in monitoring surgical treatment of this type.

Procedure

I understand that my feet will be physically examined and I will be asked a series of questions by the investigator. Computerised foot pressure measurements will be made of my feet by walking over a pressure sensitive platform.

Pre- and post-operative x-rays ordered by your podiatrist will be assessed and measurements taken from these films. No additional x-rays will be ordered by your podiatrist other than what would normally be used.

I understand that I will be asked to return for follow-up foot pressure recordings at 3, 6, 12, 18 and 24 months post-operatively. I agree that the Department of Podiatry and Curtin University of Technology are not responsible for my decision to undergo foot surgery nor do they offer any form of treatment that may influence the outcome of the surgery.

Benefits

I understand that I will receive no direct benefit from being involved in the study.

Confidentiality

I understand that the information obtained from the study will be recorded and data derived from this information will be used for teaching purposes and to produce publications in scientific or medical journals. All personal information gathered will be subject to the University's confidentiality and privacy rules and regulations.

Request for further information

I understand that I may ask for more information about the study now or at a later date as the study progresses. I understand that I will be informed of any new findings discovered during the course of the study that may influence my continued participation.

Refusal or withdrawal of participation

I understand that I may withdraw from the study at any time without prejudice to my podiatrist's or the University's continuing care. I also understand that Alan Bryant may terminate my participation in the study at any time after he has explained the reasons for doing so.

I have explained to .... the nature and purpose of the research and the procedures required to the best of my ability,

.... (Investigator) Date ....

I confirm that the nature and purpose of the research and the procedures that I will be asked to undergo has been explained to me. I have read and understand this consent form and agree to participate as a subject in this research project.

....(Participant) Date ....

....(Supervisor) Date ....

APPENDIX D

CONSENT FORM USED FOR CONTROL SUBJECTS

Title of project	Plantar pressure distribution changes with hallux valgus and hallux limitus surgery.
Investigator	Alan R. Bryant BSc(Pod), MSc.
Supervisors	Dr Paul Tinley, Head, Department of Podiatry. Associate Professor Kevin Singer, School of Physiotherapy.

Purpose of research

I have been informed that this study will investigate the differences between hallux valgus and hallux limitus and test the effectiveness of the surgical treatment of these conditions. This study should help podiatrists use plantar pressure measurement technology to evaluate forefoot deformities and the role of this technology in monitoring surgical treatment of this type.

Procedure

I understand that my feet will be physically examined and I will be asked a series of questions by the investigator. Computerised foot pressure measurements will be made of my feet by walking over a pressure sensitive platform.

Radiographs of my feet will be taken and measurements made from these x-rays.

Benefits

I understand that I will receive no direct benefit from being involved in the study.

Confidentiality

I understand that the information obtained from the study will be recorded and data derived from this information will be used for teaching purposes and to produce publications in scientific or medical journals. All personal information gathered will be subject to the University's confidentiality and privacy rules and regulations.

Request for further information

I understand that I may ask for more information about the study now or at a later date as the study progresses. I understand that I will be informed of any new findings discovered during the course of the study that may influence my continued participation.

Refusal or withdrawal of participation

I understand that I may withdraw from the study at any time without prejudice to the University's continuing care. I also understand that Alan Bryant may terminate my participation in the study at any time after he has explained the reasons for doing so.

I have explained to .... the nature and purpose of the research and the procedures required to the best of my ability,

.... (Investigator) Date ....

I confirm that the nature and purpose of the research and the procedures that I will be asked to undergo has been explained to me. I have read and understand this consent form and agree to participate as a subject in this research project.

....(Participant) Date ....

....(Supervisor) Date ....

APPENDIX E

CORRELATION OF AGE AND BODY-MASS-INDEX WITH PRESSURE/FORCE VARIABLES OF CONTROL GROUP

		AGE		BMI		
	Region	Pearson Correlation	Sig.(2-tailed)	Pearson Correlation	Sig.(2-tailed)	N 30
Peak pressure	MH1	-0.185	0.328	-0.075	0.695	
	MH2	0.083	0.662	-0.037	0.845	
	MH3	0.223	0.236	-0.076	0.689	
	MH4	0.048	0.802	-0.121	0.525	
	MH5	-0.105	0.580	-0.125	0.511	
	HX	0.049	0.796	-0.129	0.497	
Pressure-time-integral	MH1	-0.175	0.356	-0.164	0.387	
	MH2	0.140	0.462	-0.002	0.992	
	MH3	0.213	0.258	0.014	0.941	
	MH4	-0.088	0.645	-0.107	0.575	
	MH5	-0.172	0.363	-0.153	0.420	
	HX	-0.079	0.680	-0.265	0.156	
Contact time	MH1	0.046	0.811	-0.234	0.213	
	MH2	0.081	0.671	-0.186	0.325	
	MH3	0.090	0.636	-0.211	0.263	
	MH4	0.114	0.547	-0.103	0.587	
	MH5	0.058	0.760	-0.015	0.937	
	HX	0.098	0.605	-0.338	0.008	
Maximum force	MH1	-0.331	0.074	-0.153	0.421	
	MH2	0.148	0.437	0.000	0.999	
	MH3	0.319	0.086	0.012	0.951	
	MH4	-0.006	0.993	-0.086	0.652	
	MH5	-0.127	0.505	-0.154	0.416	
	HX	-0.114	0.548	-0.094	0.621	
Force-time-integral	MH1	-0.305	0.101	-0.269	0.150	
	MH2	0.089	0.640	-0.049	0.798	
	MH3	0.217	0.249	-0.018	0.924	
	MH4	-0.103	0.587	-0.123	0.518	
	MH5	-0.167	0.377	-0.173	0.362	
	HX	-0.020	0.299	-0.222	0.239	

MH = metatarsal head, HX = hallux

APPENDIX F

INDEPENDENT SAMPLES t-TEST RESULTS OF GENDER Vs PRESSURE/FORCE VARIABLES OF CONTROL GROUP

	Region of foot	t	df	Sig. (2-tailed)	Mean difference (Γ-E)
Peak Pressure	MH1	-0.832	28	0.412	-3.41
	MH2	-1.885	28	0.070	-11.2
	MH3	-1.332	28	0.193	-5.68
	MH4	0.230	16	0.821	0.80
	MH5	-0.004	28	0.997	-2.22
	HX	-0.381	28	0.706	-2.42
Pressure-time-integral	MH1	-1.020	28	0.316	-1.27
	MH2	-1.827	28	0.078	-3.01
	MH3	-1.149	28	0.260	-1.55
	MH4	0.317	15	0.755	0.42
	MH5	0.141	28	0.889	0.26
	HX	-0.769	28	0.448	-1.31
Contact time	MH1	0.982	28	0.335	2.31
	MH2	0.149	28	0.884	0.36
	MH3	0.371	28	0.714	0.92
	MH4	0.455	28	0.652	1.13
	MH5	0.352	28	0.728	0.93
	HX	0.733	28	0.470	2.86
Maximum force	MH1	1.727	28	0.095	4.38
	MH2	-.0540	28	0.593	-1.12
	MH3	-0.144	28	0.887	-0.20
	MH4	0.952	28	0.349	1.33
	MH5	0.560	28	0.580	0.63
	HX	1.281	28	0.211	3.88
Force-time-integral	MH1	0.952	28	0.349	0.93
	MH2	-0.598	28	0.555	-0.41
	MH3	-0.200	28	0.843	-0.12
	MH4	0.780	28	0.442	0.46
	MH5	0.270	28	0.789	0.12
	HX	0.702	28	0.488	0.61

MH = metatarsal head, HX = hallux

APPENDIX G

CONTROL GROUP MEAN RAW DATA

Subject	OppMH1	OppMH2	OppMH3	OppMH4	OppMH5	OppHx	OptiMH1	OptiMH2	OptiMH3	OptiMH4
1	28.2	27	24.8	19.2	14.2	30.7	9.6	9.2	8.1	6.6
2	18.5	22.2	20.5	15	6	22.7	5.7	6.6	6.7	5.5
3	23.5	88.3	32	15.7	13.5	51	7.2	20.4	10.1	5.4
4	20.8	51.8	42	15.2	15	36.3	6.3	14.1	12.5	5.4
5	14.8	25.8	25	13.3	11.7	45.5	5.2	8.2	8.2	4.8
6	29.7	28.5	24.5	13.3	7.3	35.7	10.7	9.9	8.7	4.7
7	24.5	46.5	24.2	13.7	6.8	42.3	9.1	14.1	9.7	5
8	32.7	23.2	16	9.7	16.5	81	9.4	7.7	6	3.5
9	29	24.3	22	13.3	12.5	59.7	7.3	7.9	7.3	4.8
10	27	36.3	33	35.3	43.7	51.2	8.4	11.4	12.4	15.3
11	24.5	28.7	31	40	47.8	49	7	8.1	12.1	15.3
12	58.7	38.5	29.7	19.3	10.5	61.8	17.1	11.1	9.7	7.2
13	23.8	53.2	38.8	18.8	7.7	32.8	8	14.5	11.2	6.1
14	36.2	54.5	57.2	35.5	64	44	11	17.3	18.7	13
15	49.5	66.3	72.2	30	48.5	78.2	14.8	20.5	22	11
16	36	54.5	44.2	20	41.2	15.5	9.2	13.2	11.7	6.9
17	26.7	35	30.3	21.2	30.2	28.3	7.2	10.1	9.2	6.7
18	23.8	35.8	31.2	25.3	29.7	38.3	7.2	10.3	9.5	8.2
19	20.7	41.7	47	21.8	12.7	36.2	5.9	11.2	12	6.6
20	16	29.7	36.3	18.2	18.2	60.7	5	8.3	9.4	6
21	30.3	55.3	48.5	34.7	39.3	57	10.9	14.6	13.8	11
22	57	44.3	39.2	23	21.8	41.7	18.7	13	11.6	7.9
23	18	34	35.2	35	23	26	5.1	9.9	10.3	9.9
24	23	30	29.8	20.2	9	69.2	8	11.2	11.2	6.8
25	20.7	65.2	44.2	18.8	15.3	56.5	8.3	23.6	19.5	7.5
26	24.5	76.7	31.5	12.8	13.5	76.5	8.4	23.9	12.6	4.8
27	22.2	38	36.7	25.7	48.2	34.5	7.6	12.4	12.1	11.6
28	24.5	38	37.3	26.3	25.8	34.3	7.9	14.7	14.6	11.4
29	18.3	31.5	25	24.8	10.8	37.3	5.4	9	8.8	8.5
30	15.8	24.3	29.2	34	21.5	32.7	4.8	7	8.9	9.7
31	21.5	36.2	37.8	40	33.2	24.5	7.2	10.9	12.2	13.3
32	40	27	27.2	25.2	23.5	45	11.4	8.7	9.2	8.8
33	45	46.7	54.3	22.8	16.8	45	16.5	15	15.5	7
34	27.8	40.5	42.8	27.8	9.8	26.2	11	12.7	12.4	7.5
35	39.3	30.8	28.7	17.7	12	45.2	11.7	9.5	9.2	6.2
36	36	33.5	36.2	28.7	17.8	24.2	11.8	10	10.7	9.4

OptiMH5	OptiHx	OctMH1	OctMH2	OctMH3	OctMH4	OctMH5	OctHx	OmfMH1	OmfMH2	OmfMH3
4.4	7.2	84.3	84.3	86.9	85.2	79.9	78.6	37.1	24.5	20.6
2.2	5.9	54.9	56.9	58.8	58.8	54.9	54.9	21.1	17	19.1
5	9.7	80.5	85.6	87.7	86.6	87.7	62.5	15.9	36.3	17.8
4.1	9.1	81.3	82.2	85.1	85.1	73.8	70.2	22.5	37.1	27
3.4	10.3	84.3	85.4	87.5	87.6	84.6	82.4	19	20.2	21.4
2.9	11.7	76.1	76.9	80.2	76.9	73.6	64.5	33.2	26.3	20.2
2.4	16	76.1	78.5	79.3	78.5	67.3	76.9	28.6	27.9	20.2
5.2	19.9	76.8	77.7	79.6	73.4	79.5	78.5	36.5	18.8	14.8
4.3	13.3	70.9	72.7	75.5	77.3	76.4	72.7	33.6	22.2	19.1
14.9	10.5	87	89.8	91.7	89.9	84.3	62.7	22.2	23.3	24.4
16.3	9.7	86	86	88.7	90.4	86.9	56	19.1	16.1	21.1
4.3	13.6	69.5	70.8	72	70.8	71.2	72.9	30.9	22.5	19.9
2.8	5.7	78.7	82.3	84	81.1	83.2	64.8	23.4	32.6	24.2
19.5	8.8	84.5	85.9	90.2	90.1	84.5	74.6	22.3	22.6	26
14.1	16.9	85	88.7	91.6	86.9	84	79.3	25	24.2	26.9
10.5	3.8	77.9	81.5	84.3	84.3	78.7	56.5	17	35.7	22.1
6.2	5.2	75.8	82.1	83.9	85.8	79.5	58.1	19.6	21.3	17.2
7.4	7.3	76.9	83.8	86.3	84.6	78.6	59.8	14.1	18.9	17.2
4	5.8	81.9	86.2	87.1	86.2	82.5	58.8	20.8	34.1	28.6
5.5	13.2	80.2	83	86.8	85.8	83.9	72.5	19.2	24.8	23.9
10.9	17	81.4	81.4	87.6	84.1	82.3	82.3	20.7	22.8	26.6
6.8	10.8	87.1	88.8	89.6	86.3	83.1	90.3	36.2	22.3	21.7
6.2	5.4	80.8	83.6	86.3	87.7	83.5	86.3	13.1	21.9	25.2
3.3	14.8	83.2	85.9	86	84.5	78.9	86	16.6	22	21.4
5.5	12.4	82.6	86.1	87.8	86.9	86.9	55.8	18.6	28	28.8
4.3	22.8	81.1	83.8	86.5	83.7	86.5	73.9	19.8	25.6	20.3
16.4	10.8	81	86.2	86.2	84.5	77.6	78.5	17.5	25.8	23.9
12.5	10.3	83.4	88.9	88.9	88.9	89.7	67.8	15.3	27.1	27
4.1	9.3	81.5	84.5	86.4	84.5	78.6	73.8	18.7	26	24.5
6.2	8.6	78.2	82.2	86.2	86.2	83.2	59.4	15.4	21.3	23.7
11.1	5.8	82.3	86.1	86.1	88.6	87.3	73.3	21.1	23.7	30.8
8	14.3	56.8	56.8	91	59.3	58.6	60.3	34.7	23.6	24.5
4.2	8.9	86.5	87.4	88.3	82.9	82	68.4	28.1	27.4	28
3	5	83.5	84.4	86.2	86.2	82.5	78	24.4	27.6	30.6
4.6	10.6	81.6	82.5	83.5	85.3	81.7	74.3	28.4	24.9	22.4
6.4	6.5	80	80	83.5	84.4	81.8	64.3	26.6	22.6	27.7

OmfMH4	OmfMH5	OmfHx	OftiMH1	OftiMH2	OftiMH3	OftiMH4	OftiMH5	OftiHx	24ppMH1	24ppMH2
11.8	5.1	26.1	12.9	9.1	8.6	5.1	1.8	5.7	29.2	27.8
8.6	3.9	18.3	7	6.7	6.7	3.7	1.1	4.1	38.3	26.5
11.8	6.9	24.9	4.6	10.5	6.3	4	2.2	4.5	19.3	82.5
12.1	5.9	16.2	6.1	11.8	9.3	4.2	1.8	3.8	32.2	38.5
10.7	7	18.5	6.5	7.6	7.8	3.6	1.9	4	16.5	29.5
11	6.2	21.6	12.3	9.6	7.2	3.7	1.7	6.3	28	33.2
11.1	5.1	27.2	11.2	11.3	7.6	3.4	1.2	8.9	24.5	54
9	6.8	44.4	11	7.2	5.1	2.8	2.2	11.5	37.2	27
13	7.9	39.7	8.6	7.6	6.4	4	2.2	9	41.3	27
21.3	12.5	24.2	6.6	8	9.5	8.6	4.2	4.6	29.3	32.7
25	15.1	21.4	5.4	5.1	7.7	9.4	5.4	4.1	32	31.5
12.6	3.9	26.1	10	7.7	7.2	4.7	1.5	5.4	52.3	38.2
11.8	3.3	16.1	7	10.6	7.6	3.7	1	2.7	24.2	52.8
15.7	11.8	14.5	7.1	7.8	9.3	6.2	4.2	3.2	35.5	47
12.6	10.6	14.7	8.5	9.1	9.9	5	3.6	3.4	33	77.2
12.5	10.9	9.3	4.7	10.2	7.2	4.2	3.2	1.8	34.8	53.7
10	6.1	10.8	4.8	6.1	5.5	3.4	1.8	1.9	26.2	34
12.6	7.1	15.1	3.9	5.8	5.7	4.2	2.2	2.8	22.2	39.2
15.3	6.4	13.5	5.7	9.6	9	5	1.9	2.2	21.7	41.2
16.2	9.5	26.4	5.7	7.4	7.8	5.5	3	5.5	18.8	32.7
16.8	9.6	13.1	7	7.7	9	6.4	3.4	4	36.7	52.5
13.2	6.9	14.1	12.4	7.7	7.5	5.1	2.6	3.5	31.2	57.7
18.3	8.8	16.3	3.5	6.9	8.2	5.9	2.5	2.9	27.5	31.8
11.4	4.4	28.9	6.1	8.4	7.8	3.9	1.4	6.1	20.3	34
15.4	7	21.1	6.8	11.3	11.5	5.1	2.2	4.6	22.3	54.3
9.6	3.8	32.8	7.4	10.3	7.8	3.2	1.2	9.3	25.2	66.3
14.3	13.2	22.5	5.7	9.5	9.5	5.7	4.7	6.2	24.3	37.7
15.1	10.1	15.6	5.3	11.2	11.9	7.4	4.6	4.3	31.2	37
15.8	6.4	28.2	5.2	8.5	9	6	2	5.5	16.3	25.8
20.2	8.4	26.6	4.8	6.5	7.8	6.6	2.4	5.5	22.8	19.7
33.3	17.3	16.3	6.6	7.7	10.4	11.6	5.5	3.2	29.3	30.7
22.6	12.2	25.3	10.4	7.6	8.2	7.8	4.2	6.9	34.5	24.8
11.5	3.7	23.4	10.9	10.3	9.7	4	1.2	4.7	52.3	40
14.6	4	16.6	8.6	9.4	9.5	4.4	1.1	3	31.8	34.7
13.3	5.9	22.6	9.4	8.5	4.7	7.7	2	5.1	47.5	34.7
18.5	7.9	10.5	9	7.7	9.5	6.7	2.9	2.8	39.3	37

24ppMH3	24ppMH4	24ppMH5	24ppHx	24ptiMH1	24ptiMH2	24ptiMH3	24ptiMH4	24ptiMH5	24ptiHx	24ctMH1
25.8	22.2	8	28.2	9.3	9.1	8.5	7.5	3.2	5.7	85.8
21.4	12.5	6.7	31.4	8	8.4	8	6.2	2.8	8.5	78.5
41	14.3	9.2	43.7	6.3	19	11.1	4.7	2.5	10	79.4
32	13	10.8	37	8	12.5	10.9	5	3.5	9.1	80.9
27.2	15.2	10.2	48.3	5.9	8.6	8.4	4.9	3.4	11.2	86.3
24.5	14	9.2	32.2	7.7	9.3	8	4.4	3.2	9.6	80
26	16.2	7	32	7.4	13.7	9	5.4	2.2	9.3	79.6
17.8	9.8	14.3	63.8	9.7	8.3	6.1	4	4.9	15.8	82.2
20.7	13.3	10.7	51.2	8.9	8.5	6.6	4.6	4.1	11.4	78
29.3	23.7	26.3	38.8	10.6	10	8.6	7.9	7.8	7.6	86.2
26.3	24.8	23.3	61.5	9.6	8.6	9.1	9.5	8.8	13.9	90
26.8	18.2	9.8	57.5	17.4	11.6	9.6	7.3	4.3	13.6	82.4
39.8	17.5	7.8	29.2	6.8	12.8	10.1	5.1	2.5	4.8	76.7
49.8	29.7	48.5	41.8	10.8	15.9	16.8	10.9	15.7	9.2	79.9
81.2	26.2	43	61	10.3	19.8	21.1	9.2	12	13.4	79.8
42.2	21.3	34	17.2	9	12.4	10.8	6.8	8.3	3.9	79.6
31.3	23.7	17.5	38.3	9.2	12	11.4	8.7	6.4	11	82.8
37	29.2	27.2	38.8	9.1	14.9	14.8	12.5	12.4	11.9	84.4
40.2	17.8	8.7	34	6.1	11	11.3	5.8	3	5.7	80.2
39.5	17.5	17.3	39	5.2	9.1	10.5	5.7	4.9	7.3	76.1
40.5	25.3	27	77.8	12.5	12.9	11.7	8.6	7.7	19.7	84.8
35	16.8	22	80.8	10.1	11	8.6	5.5	6.4	20.7	81.9
31.2	26.8	11.2	44.8	7.3	9.6	9.4	8	3.8	8.8	84.9
35	25.7	23	30	6.1	10.4	10.5	7.1	5.5	5.6	80.2
40.3	15.2	13	47.5	7.2	17.7	15.5	5.8	4.5	9.2	82.7
37.8	13.5	9	57.3	8	19.8	12.4	4.6	2.6	15	77.7
34.3	25.2	40.5	32.8	7.1	11.2	10.7	10.7	13.7	8	78.4
36	20.5	15.7	44.2	7.8	12	11.6	7.6	6.7	9.9	82.1
22	21.8	10	39.2	5.3	8.3	8.1	7.8	4.1	10.3	82.6
17	15	8	46.7	7.6	6.5	6.3	5.6	3.1	15.5	80
30.5	30.7	23.2	31.7	11.9	12.5	12.9	12.9	10.4	10.8	83
24	22	21	49.8	13.4	10.1	10.2	9.7	9.2	18.4	83.1
44.3	21	12.2	55.3	19.3	13.4	13.5	6.6	3.7	10.3	85.6
35.5	26.3	8.2	30.2	12.8	12.1	11.9	7.5	2.9	6.4	82.9
33.7	19.8	14.7	41.5	13.1	10.1	10	6.8	5.2	9.2	82.1
35	27	15	25.7	16.6	11.8	11.8	9.8	6.2	7.2	82.2

24ctMH2	24ctMH3	24ctMH4	24ctMH5	24ctHx	24mfMH1	24mfMH2	24mfMH3	24mfMH4	24mfMH5	24mfHx
86.7	87.7	88.7	81.1	80.2	35.8	27.8	23.5	12.6	4.5	19.5
81.5	84.6	83	80	76.9	38.3	26.5	21.4	12.5	6.7	31.4
83.4	86.3	85.3	79.3	83.3	18.7	34.9	20.8	8.5	4.1	21.3
83.6	855	82.8	70.9	80.9	27	30.6	22.2	11.2	5.7	16.1
88.4	89.5	87.4	86.3	87.4	20.9	21	22.2	10	6.8	17.8
81	83	83	80.1	79	33.8	26.4	20.9	11.6	7.1	20.6
86.4	85.4	83.4	77.6	72.7	28.5	29.9	21.6	11.8	5.3	20.6
82.2	84.1	86	85	84.1	38.4	19.5	13.8	8.6	7.2	37.8
78.9	81.7	81.7	80.7	77.2	38.3	23.6	17.4	11.4	7.3	32.9
86.2	89.9	89.1	84.5	53.1	26.8	22.8	20.3	15.8	7.5	18.4
88.9	93	91.9	88.9	75.7	25.1	17.1	17.4	15.6	7.9	20.2
83.2	87.4	84.9	85.7	86.6	28	20.8	19	12.8	4.1	25.8
80.6	80.6	81.6	82.5	61.2	26.4	32.6	23.8	11.4	3.7	17.1
81.7	86.3	88.1	80.7	65.2	22.8	20.4	23.5	12.7	10.2	13.8
82.7	85.6	84.6	84.6	74.9	20.1	26.2	24	11.2	10.5	16.4
83.5	85.4	82.5	77.7	66.2	19.4	35.4	24.6	13.2	9.8	8.6
84.5	87.1	87.9	86.2	79.3	21.7	23.4	20.1	12.3	6	13.1
84.4	87.3	88.8	88.1	78.7	19.3	22.6	24.1	14.6	8	7.9
86.5	88.3	86.5	79.3	62.1	21.2	33.1	27.8	12.1	5	11.6
81.4	84.1	83.2	77	61.1	21.1	25.2	25.2	14.7	8.2	16.5
86.7	89.6	88.6	84	88.6	22.1	17.3	18.3	13.8	7.3	18.9
83.8	85.9	83.8	83.9	87.6	22.7	17.8	14.4	10.7	7	29.9
85.8	85.9	84.9	78.4	81.1	23.2	22.9	22.4	12.2	5.3	22.5
82.9	84.7	85.6	79.2	61.4	13.3	22.8	25.6	16.7	9.3	15
85.4	89.2	84.6	85.6	58.3	21.8	25.7	24	12.2	5.4	18
78.6	84	82.2	80.3	68.9	19.1	24.2	21.7	10.3	2.9	24.1
83.1	85.9	84.1	76.5	76.4	19.3	26.4	23.4	13.7	11.5	20.8
88.7	89.6	85.8	82.1	71.7	19.9	28	24.6	13.2	8	19.8
84.4	85.3	84.4	78.9	79	17.3	23.9	23	15.2	5.5	25.7
80	82.7	80	73.7	80.9	23.9	18.8	16.5	10.9	3.6	35.1
83.7	85.7	87.8	84.4	86.4	24.2	20.9	26.1	24.3	11.5	17.2
85.3	86.3	86.3	86.3	74.6	27.5	20.1	21.3	20	12.9	25.1
86.5	86.5	81.1	82	72.1	31	27.6	25.4	10.5	4.2	25.7
89.2	86.5	83.8	80.2	73.8	27.1	25.8	26.8	13	3.5	18.3
84.9	85.9	87.8	83	71.3	29	26.9	25.8	15.1	6.5	20.8
82.2	84.8	85.6	83.9	73.7	28.1	26.1	27.1	18.6	6.9	10.9

24ftiMH1	24ftiMH2	24ftiMH3	24ftiMH4	24ftiMH5	24ftiHx
11.7	9.6	8.9	5.2	1.6	4.1
10	8.1	7.7	4.2	1.5	6.3
5.7	10.3	6.9	3	1.3	4.3
7.3	10.9	8.3	3.9	1.6	3.9
7.3	8.1	7.8	3.8	2	4.1
9.6	8.9	6.9	3.4	1.8	5.1
8.8	10.4	7.5	3.6	1.3	5
10.2	6.9	5.2	3	2.3	9.5
9.4	7.8	5.6	3.8	2.3	6.8
8.8	7.2	6.4	5.2	2.6	3.3
7.7	5.7	6.3	5.9	2.9	4.5
10	7.7	7.3	5	1.6	5.6
6.5	9.1	6.9	3.3	1.1	2.6
7.5	7.5	8.9	5.2	3.5	3.2
6.8	8.9	8.8	4	3	3.6
5.1	9.6	7.4	4.3	2.7	1.6
7.5	8.5	7.5	4.8	2.2	3.2
7.7	9.4	10.5	7.1	3.8	2.3
5.9	9.5	8.9	4.1	1.6	2
5.7	7.2	8	4.9	2.4	3.2
7.7	6.1	6.7	4.9	2.4	4.6
7.5	5.5	4.9	3.6	2.1	7.2
6.2	7.5	7.3	4	1.6	4.3
4.3	7.3	7.8	4.9	2.4	2.7
6.4	9.4	9.3	4	1.8	3.5
6.7	9.2	7.4	3.1	0.8	6.1
5.9	8.8	8.4	5	3.8	4.5
5.7	9.3	9	5.2	3	4.4
5.5	8.3	8.6	6.1	1.9	5.3
7.9	6.6	6.3	4.2	1.2	8.7
10.1	9.6	12.1	11.3	5	5.5
11.5	8.5	9	8.6	5.4	8.4
11.7	10	9.1	3.8	1.3	5.1
9.8	9.1	9	4.3	1.1	3.6
9.5	9.1	8.8	5.3	2.3	4.4
11.7	10.1	10.5	7.2	2.8	3.1

pp = peak pressure, pti = pressure-time-integral, ct = contact time, mf = maximum force, fti = force-time-integral
MH1 = 1st metatarsal head, MH2 = 2nd metatarsal head, etc, Hx = hallux.

APPENDIX H

HALLUX LIMITUS GROUP MEAN RAW DATA

Subject	Gender	Age	BMI	0ROM	0df	0pf	0ppMH1	0ppMH2	0ppMH3	0ppMH4
1	2	48	24.98	70	45	25	22	29.2	26	17.8
2	2	48	24.98	80	50	30	14.7	43.5	42.2	42
3	1	59	33.75	15	15	0	19.3	39.2	50	64.3
4	1	66	25.69	20	12	8	24.5	35.3	39.7	35.3
5	1	50	27.78	32	32	0	54.5	31.8	39.2	42.7
6	2	52	20.17	60	30	30	18.8	29.2	28.2	23.5
7	2	36	19.81	45	30	15	19.5	27	26.3	22.2
8	2	53	18.59	45	35	15	17.5	25.5	25.5	22.7
9	2	53	18.59	45	35	15	19.5	27.3	22.2	17.8
10	1	39	25.71	50	35	15	19.5	38.8	36.7	32.7
11	2	46	34.1	40	30	10	25.8	46.5	59.5	57.5
12	2	47	26.5	50	40	10	32.7	21.3	27.3	27.8
13	2	47	26.6	32	25	8	13.3	22.2	26.2	25.3
14	2	56	28.94	14	12	2	22.5	37	34.2	24.3
15	1	62	25.58	35	25	10	28.7	49.2	47	35.2
16	1	62	25.58	45	35	10	11.7	35	47.5	41
17	2	53	24.98	25	20	5	21.5	37.5	42.2	37.2
18	2	53	24.98	24	18	6	19.7	38.5	43.3	51.3
19	2	61	23.79	37	35	2	47.8	33.5	35	30.8
20	1	49	25.24	40	40	0	21.7	59	49.5	27.3
21	2	43	32.03	55	40	15	21.8	33	33.2	29.8
22	2	43	32.03	40	30	10	20.8	36.5	36.2	29
23	1	39	30.25	48	40	8	20.3	67.5	41.8	22

OppMH5	OppHx	OptiMH1	OptiMH2	OptiMH3	OptiMH4	OptiMH5	OptiHx	OctMH1	OctMH2	OctHM3
6.5	79	7.3	9.6	9.3	6.7	2.4	17.7	79.6	82.5	85.4
15.3	20.5	4.4	12	12.3	12.2	5.1	4.7	81.4	86.3	88.2
53.7	56.2	5.7	12.6	15.5	19.1	17	13.3	75.5	83	85.8
30	26.7	7.5	11.7	12.9	12.4	10.1	4.5	74.8	79.1	82.6
19.7	99.7	19.4	11.3	15.2	17.7	7.8	28.7	84.7	83.9	83.8
10.8	61	5.5	9.1	9.6	8.4	4.3	16.1	73.7	78.7	82.1
19.3	49	6.6	9.8	10.2	8.9	6.3	10.4	74.6	78.1	80.7
24.8	26.5	4.8	7.3	7.8	7.3	6.8	6	82.4	86.1	88
22.3	28.5	5.3	7.8	7.2	6.5	7.3	5.8	83	85.1	88.1
22.5	33.3	4.7	10.6	11.3	10.5	8.3	6.9	64.2	77.2	79.8
34.8	9.5	8.5	14.5	17.2	15.5	9.6	1.2	76	82.3	84.8
16.3	67.3	8.7	6.9	9.8	9.8	5.6	21.2	80.4	83.2	85.1
25.7	94.5	4.3	7.3	9.6	9.6	9	17	75.7	80.4	82.3
12.8	79.3	7.3	11.7	11.3	8.3	5.1	18.6	74.7	80.1	81.9
22	64.2	9.1	15.1	14.8	11.5	7.6	17.8	70.3	75.6	81
32.8	48.2	3.9	12.2	15.7	15.2	13.4	11.6	71.9	78.1	87.7
31.2	16.2	5.5	10.6	12.8	12.5	11.1	2.1	73	82.9	86.6
52	11.7	5.8	10.8	12.8	13.2	12.5	1.6	72.3	83.4	88
29.7	47.7	13.9	10.8	10.6	8.8	8.9	13.1	83.6	86.4	86.4
11.2	51.3	7	15.3	13.7	9.1	3.8	10	75.3	81.4	84.5
15	67	6.4	9.3	9.4	8.6	5.1	12.9	83.3	91.7	91.7
15	83.5	5.9	10	10	8.3	4.6	14.4	79.4	79.4	79.4
15.8	31.2	7.9	20.2	13.8	10.2	8	10.8	81.9	83.5	88.2

OctMH4	OctMH5	OctHx	0mfMH1	0mfMH2	0mfMH3	0mfMH4	0mfMH5	0mfHx	0ftiMH1	0ftiMH2
82.5	81.6	81.6	22.3	26.3	22.5	11.1	3.3	49.1	6.8	8.2
90.2	85.3	61.5	13.1	30.9	37.6	23.5	7.1	9.8	3.3	9
88.7	87.8	78.3	7	14.8	19.7	21.2	11.5	20.3	1.9	4.6
83.5	80.9	59.9	12.7	26	32.7	25.4	13.7	21.7	3.6	8.5
84.7	80.4	85.5	26.7	16.7	21.5	19.7	3.8	30.9	9.6	5.8
83	82.1	70.3	19	27.9	29.4	17.5	5.8	26.3	4.9	8.3
85.1	82.5	57.2	21.6	25.3	25.2	19	10.1	36.6	6.6	9.5
89.9	90.8	66.6	18.3	25.7	25.6	16	8.4	22.5	4.7	7.4
91.1	91.1	64	20.8	26.9	23.7	14.9	11.1	28.7	5	7.9
83.3	82.4	60.7	14.3	25.2	29.7	20.2	9.9	18.3	2.8	6.8
81.1	78.5	37.9	12.4	27.9	36	26.1	11.8	4.9	3.8	8.9
85.1	77.6	84.1	30.5	18.9	21.4	14.6	5.7	31	8.6	5.9
89.7	88.8	89.7	13.9	17.1	24.7	20.3	11.2	21.4	4.2	5.4
84.7	82	71	20.5	25.6	25.2	13.4	5.1	28	6	8.5
83.8	81.9	66.7	26.4	27.5	27.8	18.9	8.1	27.5	7.2	9.6
84.2	83.4	70.1	6.4	16.6	27.9	28.2	13.3	25.2	1.8	6
88.3	89.3	45.7	20.6	29.5	34.7	26	9	10	4.6	8.3
88.9	89.8	54.8	17	28.8	34.4	32.1	15.9	6.1	5	8.5
87.5	85.5	85.3	33.3	21.3	20.6	12.4	7.3	21	9.6	6.9
84.5	81.4	57.7	18.5	32.6	25.5	12.3	5.1	22.2	5.2	10
91.7	91.7	83.3	17.4	18.9	25.9	15.6	6.9	27	5.7	5.7
79.4	79.4	79.4	16.7	20.3	27.9	16.1	6	37.6	4.3	5.8
89.8	87.4	78	12.8	24.5	19.8	16	8.2	12.3	4.8	8.9

0ftiMH3	0ftiMH4	0ftiMH5	0ftiHx	3ppMH1	3ppMH2	3ppMH3	3ppMH4	3ppMH5	3ppHx	3ptiMH1
7.6	3.9	1.1	10.5	31	42.5	38.3	22.5	8	33.7	11.4
11.6	7.9	2.6	2	25.8	33	31	26.8	14.5	7.8	9.7
6.6	6.9	3.3	4.2	23.2	49.6	43.4	30.8	18.4	31	7.9
11.3	8.9	4.3	2.8	23.2	49.6	43.4	30.8	18.4	31	7.9
7.6	7.5	1.5	8.4	23.2	49.6	43.4	30.8	18.4	31	7.9
10	6.8	2.2	6.7	17.3	31.2	41.3	37.8	23.2	10.8	4.3
10.2	6.5	2.6	7.9	23.7	35.8	43	35.8	23.5	4.2	6.9
8.4	5.4	2.8	4.9	22.5	34.3	29.3	30.5	24.2	15.8	5.3
8.1	5.7	3.8	5.4	21	38	28.3	19.3	21.3	19.3	5.8
9.5	7.3	3.6	3.5	28.7	63.3	51	35	19	24.3	9.3
11.8	8.3	3.4	0.3	31.2	47.8	46.3	35	20.2	80.5	10.7
7.1	5.2	1.9	7.8	13.3	32.2	40.8	44	24	37.7	5.1
8.5	7.3	3.8	4.7	17.5	41.2	34.8	31.5	19.3	115.3	6.2
8.7	4.8	1.8	6.2	27.5	74.2	59.8	26.5	10.2	41.2	11
9.9	6.9	2.5	7.4	29.8	60.3	53.3	29.7	17.7	26.2	9
10.8	11.2	5	5.7	21.7	37	45.7	38.7	29.5	21.8	6.2
11.5	9.8	3.9	1.2	23.2	49.6	43.4	30.8	18.4	31	7.9
11.3	10.4	4.9	0.6	23.2	49.6	43.4	30.8	18.4	31	7.9
6.8	4.1	2.3	5.3	23.2	49.6	43.4	30.8	18.4	31	7.9
8.7	4.7	1.6	4.3	22	93.2	55	21.3	11.8	28.8	7
8	5.2	2.1	6.2	28.7	44	41.3	32.3	12.3	19.7	11.1
8.3	4.8	1.7	6.6	15.5	55.2	51	34.2	16.8	26.8	8
8.4	7	3.2	3.6	17.8	79.5	48	23.2	16.8	13.8	7.9

3ptiMH2	3ptiMH3	3ptiMH4	3ptiMH5	3pitHx	3ctMH1	3ctMH2	3ctMH3	3ctMH4	3ctMH5	3ctHx
15.3	14.5	9.8	3.5	7.7	76.5	82.1	82.9	81.3	78.1	62.9
11.5	10.9	9.3	4.9	1.4	74.7	78.3	80.7	81.9	83.2	48.2
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
8.6	11.1	10.2	6.6	0.9	72.7	79.2	85.8	84	82.1	31.4
10.7	12.7	11.4	8.5	0.4	70.8	78.4	82.4	83.9	79.1	21.1
8.5	8.6	9.6	8.1	2.2	74.6	77.4	80.4	84.1	84.2	35.7
9.4	8.3	6.4	7.2	3.2	78.7	81.6	83.5	87.4	86.4	52.6
16.5	15	11.5	6.5	3.7	82	86.5	86.5	89.2	88.3	50.4
16.4	16.7	12.6	6	20.3	77.5	80.5	82	82	75.9	60.4
10.6	15.7	15.8	9.1	9.7	79.3	83.8	85.6	84.7	81.1	71.2
12.4	12.8	11.6	7.5	17.6	77.3	83.6	86.4	85.5	85.5	77.2
21.8	19.2	10.5	4.2	4.7	76	80.5	84.1	84.9	83.2	37.1
16.6	15.4	10.6	7	5.8	70.2	78.6	78.6	83.3	78.6	56.5
12.2	14.6	13.4	11	5.2	78.6	78.6	78.6	87.5	87.5	55.4
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
14.4	13.8	10.7	6.6	5.8	76.6	80.8	83.3	84.9	82.4	51.3
20.6	14.7	7.3	3.5	5.2	68.3	73.8	79.4	84.9	74.6	53.2
14.3	13.7	10.9	4.7	4.6	82.6	85.4	86.3	88.1	85.3	62.6
16	15.2	11.6	6	2.8	79.9	82.6	84.1	82.6	82.6	43.5
24.2	15.9	10.2	8.2	3.3	81.9	82.8	88.3	88.2	85.1	52.8

3mfMH1	3mfMH2	3mfMH3	3mfMH4	3mfMH5	3mfHx	3ftiMH1	3ftiMH2	3ftiMH3	3ftiMH4	3ftiMH5
29.3	31.8	26.7	12.8	4.4	15.9	10.1	12.2	11.3	5.5	1.6
27.8	28.7	25.8	13.5	4.7	4.3	9.4	10.6	10.1	5.8	2.1
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
13.5	29.6	37.3	29.4	9.7	6.2	2.8	7.7	10.7	8.5	2.8
23.6	32.4	36.8	21.4	10.3	2.5	5.8	9.7	12.5	8.4	3.9
20.7	29.9	26.6	23.6	13.2	14.1	4.4	7.5	8.3	7.3	3.8
18.9	30.8	29.3	16.3	12.8	17.8	5.2	8.7	9.4	5.2	3.6
22.9	53.6	33.3	19	7.9	13.2	6.8	11.4	11.3	6.4	2.5
21	29.1	29.2	13.4	4.7	28	6.3	10.1	10.8	4.9	1.6
16.1	21.3	32	22.7	8	17.1	5.4	7.7	11.7	8.5	3.1
19.5	25.5	31.3	19.4	7.9	16.3	6.3	8.7	11.2	7.6	2.9
22.4	35.6	29.3	12.3	4.9	14.5	8.3	13.4	11.9	4.9	1.5
27.5	30.3	28	16.8	7.4	12.7	7.6	10.2	10.4	6.7	2.5
17.8	24.6	30.8	26	12.2	4.5	5	7.6	11	9.9	4.8
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
20.9	30.9	29.3	18.1	7.9	12.3	6.3	9.8	10.4	6.6	2.6
19.1	37.8	23.6	11.1	4.7	11.5	5	9.8	7.9	3.3	1.1
25.6	27.5	23	16.4	5.5	12.6	9.1	10.4	8.7	6.4	1.8
16.4	31.3	32.7	17.8	7.3	12.4	4.7	10	11.3	6.4	2
13	26.1	22.2	16	8.3	5.8	5.2	10	9.3	7.2	3.3

3ftiHx	6ppMH1	6ppMH2	6ppMH3	6ppMH4	6ppMH5	6ppHx	6ptiMH1	6ptiMH2	6ptiMH3	6ptiMH4
3.2	37.3	36.7	31.5	16.7	6.3	70.7	11.5	12.5	11.3	6.8
0.7	27.5	40.3	36.3	22.7	7.2	22.5	10.5	13.5	12.7	9.1
2.2	25.5	49.6	42.5	30	18.3	27	8.3	14.1	12.8	9.8
2.2	23	42	49	48	43.3	9.7	7	12.2	13.4	12.7
2.2	25.5	49.6	42.5	30	18.3	27	8.3	14.1	12.8	9.8
0.4	24.5	41.3	46.5	43.7	14.2	11.5	6.4	11.2	12.7	11.7
0.2	28	41.8	41.2	27.8	17.8	16.2	8.3	11.7	12.4	10.3
1.9	19.5	44	33.2	23.2	27.5	22.8	5.4	9.8	8.2	6.7
2.7	17.7	40.2	27	18.8	33.8	22.8	3.9	8.3	7.1	6.9
1.9	30.7	59	42	28.5	13.3	17.7	8.6	14.9	12.7	9.4
6.2	23.7	55.5	47.3	38.3	12.5	31.3	8.4	15.9	14.8	12
3.8	25.5	49.6	42.5	30	18.3	27	8.3	14.1	12.8	9.8
3.4	25.5	49.6	42.5	30	18.3	27	8.3	14.1	12.8	9.8
1.7	24.5	38.5	40.7	25.5	8.2	64.7	8.6	12	12.4	8.5
2.5	19.7	56.8	50	27.8	20.3	27.7	7.9	18.4	17	11.6
1	24.5	39.3	39.8	30.7	16.8	21.7	8.6	13.9	14.8	12.8
2.2	24.5	47	42.7	32.2	10.3	20.8	7.6	12.1	11.3	8.9
2.2	18.8	37.7	42.5	38.8	21	24	6.5	9.8	10.5	9.7
2.2	35.3	37	38.7	36.2	44.5	17.5	12.7	12.6	12.8	11.3
2	27	74.8	45.5	14.7	5.3	59.8	7.7	15.9	11.9	5
2.7	31.2	47.5	43.5	33.3	11.7	16	11.2	14.6	13.9	10.7
1.5	25.7	56.5	54	38.3	16.7	17	8.1	15.9	15.5	12
1.2	21.2	105.7	55.2	27	17.2	19.3	9.3	33.1	18.6	10.6

6ptiMH5	6ptiHx	6ctMH1	6ctMH2	6ctMH3	6ctMH4	6ctMH5	6ctHx	6mfMH1	6mfMH2	6mfMH3
2.4	15.5	74.4	81	81.1	78.6	66.9	64.5	35.2	31.8	22.5
3.3	4.1	78.6	80.2	82.7	82.7	82.7	58	29.8	31.2	26.9
6.2	4.6	78.5	82.3	84.6	84.8	80.6	51	21	29.5	27.6
10.8	1.1	79.7	82.4	84.3	85.2	80.5	32.9	8.2	24.8	35.4
6.2	4.6	78.5	82.3	84.6	84.8	80.6	51	21	29.5	27.6
5.6	2.2	69.2	78.9	81.7	85.6	82.7	53.8	14.5	35.5	38.6
6.1	2.1	77.1	80	82.9	84.3	80	35.7	30.4	36.6	31.3
7.1	3.6	77.2	80.1	81.1	83.2	85.1	48.1	22.8	32.4	26.5
10	3.1	80.1	84.6	86.8	90.1	90.1	48.2	14.8	35.1	25.2
5.2	2.2	77.5	82.6	82.4	79.9	76.6	38.8	20.1	32.8	28.6
3.1	7	89.7	94.4	94.4	94.4	84.1	78.6	13.8	23.3	27.2
6.2	4.6	78.5	82.3	84.6	84.8	80.6	51	21	29.5	27.6
6.2	4.6	78.5	82.3	84.6	84.8	80.6	51	21	29.5	27.6
3.3	7.3	74.8	79.3	81	80.2	80.2	43.3	22.6	21.5	25.1
8.4	7.2	73.4	76.6	80.4	82.9	80.6	56.1	15.5	26.3	26.2
8.6	3.8	74.6	78.6	84.9	87.2	84.9	54.9	22.2	24.2	24.9
4.4	2	79	82.9	85.7	85.7	80	41.9	25	31.3	28.3
6.1	1.8	80	81	83.8	82.8	82.8	24.7	18.5	26.4	31.5
14.9	4.6	85.1	87.6	86.7	88.4	83.4	59.9	24.5	20.5	22.9
1.4	8.9	69.7	77.8	81.8	74.7	53.5	56.6	25.2	32.3	19.5
4.5	3.4	86.3	88.2	91.2	92.2	89.1	71.4	27.1	28.5	26.4
5.9	2.2	82.3	85.3	87.3	87.3	82.4	43.1	15.5	33.2	33.3
7	4.7	82.7	82.7	87.4	85.8	85	60.6	13.7	32.7	23.5

6mfMH4	6mfMH5	6mfHx	6ftiMH1	6ftiMH2	6ftiMH3	6ftiMH4	6ftiMH5	6ftiHx	12ppMH1	12ppMH2
9.6	3.1	33.7	10.4	10.5	8.3	3.7	1	6.6	28.3	36.5
12.1	3.1	15.7	10.5	12	10.9	5.2	1.2	2.6	24.8	28.8
16.4	7.3	13.6	6.3	9.6	9.6	5.9	2.3	2.1	20.3	51.2
31.3	17	3.7	2.5	7.6	10.6	9.2	4.5	0.2	34.7	44.3
16.4	7.3	13.6	6.3	9.6	9.6	5.9	2.3	2.1	23.5	46.4
23.4	7	8.2	3.5	10.3	12.7	8.5	2.3	1.1	23.2	34.2
18.1	10.2	12.7	7.4	11.1	11.7	6.9	2.9	1.7	31.2	36
16.3	9.4	20.9	5.6	8.5	8	4.8	2.7	3.1	20.8	35.7
17.8	17.8	19.3	2.8	8.3	7.7	5.6	4.7	2.6	13.8	28.7
14.8	5.4	9.6	4.9	9.7	9.5	5.2	1.9	1.1	15.2	28.8
15.6	3.8	6.5	4.9	8.3	8.9	4.3	0.8	1.4	20.2	52
16.4	7.3	13.6	6.3	9.6	9.6	5.9	2.3	2.1	15.2	28.8
16.4	7.3	13.6	6.3	9.6	9.6	5.9	2.3	2.1	15.2	41
10.2	3.9	18.2	7.5	7.9	9.2	4	1.2	2.1	24.3	36.8
16.3	6.6	12.5	5.5	10.9	11.2	7.4	2.7	3.1	30	66.7
17.5	7.5	10.9	7.3	9.1	10.6	8.4	3.3	1.7	28.7	42.8
12.9	4.6	12.7	6.8	9.8	9	5.2	1.6	1	24.3	56.7
23	7.5	14.2	5.4	7.9	9.3	6.8	2.4	0.9	26.2	40.7
15	10.1	9.5	8.6	7.9	8.7	5.8	3.8	2.2	23.5	46.4
7.8	3.5	20.6	6.7	9.4	6.5	2.2	0.7	3.8	22.8	90.5
16.3	4.7	11.4	9.8	10	9.5	6.8	1.6	2.3	31.8	46.3
18.2	6.7	11.9	4.6	10.4	11.1	6.7	2.1	1.5	25.5	54.7
15.1	7.2	5.9	5.4	12.2	9.7	6.4	2.7	1.4	16.2	94.3

12ppMH3	12ppMH4	12ppMH5	12ppHx	12ptiMH1	12ptiMH2	12ptiMH3	12ptiMH4	12ptiMH5	12ptiHx	12ctMH1
31.3	18	6.3	83.8	9.5	11.8	10.7	6.9	2.2	18.2	82.1
25.8	14	4.7	44	8.8	10	9.1	5.6	1.9	9.9	76.2
65.3	64	42.7	39	6.5	15.9	18.9	19.6	14.3	3.3	81.2
43	33	18.8	13.3	11.6	14.7	14.3	10.4	5.8	1.5	82.7
40.5	28.2	15.1	42.3	7.7	13.4	12.4	9.3	5.1	7.6	78.7
33.2	26.2	9.8	41.5	6	9.5	9.7	8.3	3.9	8.2	80.2
39	24	10	14.5	10	11.5	12.2	9.2	3.9	2.5	74.7
25	19.8	22.5	18	4.7	7.4	6.1	5.1	5.9	2.6	79.6
24.2	14.3	19.2	25	4.5	7	6.3	4.3	4.2	6	79.5
26.5	24.7	12.3	56.3	4.7	8.4	10.2	8.9	4	13.5	77
43.3	37.8	13.8	99	6.5	12.7	11.9	10.5	3.5	21.7	78.1
26.5	24.7	12.3	56.3	4.7	8.4	10.2	8.9	4	13.5	77
34	29.7	17.5	56	5.1	11.5	11.7	10.6	6.9	9.4	79
38.3	25	8.8	102.3	9	12.1	12.7	9.3	3.7	12.7	78.3
53.7	20.8	11	43.5	10.4	18.6	16	8.2	4.2	9.9	73.4
42.2	32.8	16	32.7	9	12.9	13.5	11	6.7	5	71.8
48.3	30.3	15.7	20.2	7.8	14.7	13.8	10.4	6.2	1.2	81.2
45.8	41.3	22.5	18	9.3	12.3	12.6	10.4	6.2	1.4	78.3
40.5	28.2	15.1	42.3	7.7	13.4	12.4	9.3	5.1	7.6	78.7
56.5	20	11.8	44	7.5	21	14.6	6.4	2.8	5.5	77
44.2	28.3	10.5	28.8	10.7	13.6	13.2	9.5	3.9	5	85.7
52.2	36.3	12.8	38.8	7.9	15.2	14.9	11.2	5	4.4	79.8
52.2	28	18.3	13.3	7.2	31.5	17.3	10.8	7.9	3.3	79.2

12ctMH2	12ctMH3	12ctMH4	12ctMH5	12ctHx	12mfMH1	12mfMH2	12mfMH3	12mfMH4	12mfMH5	12mfHx
82.1	82.1	82.1	72.6	68.5	28.2	31.5	23.5	10.7	3.2	36.8
81	81	81	81	71.4	28	25.4	18.6	7.6	2.2	29.6
86.6	86.6	85.7	86.6	28.5	10	20	27.1	22.9	11.2	8.8
87.5	87.5	87.5	78.6	26.2	22.9	33.9	33.2	19.5	7.8	8.4
83	84.2	84.9	81.6	53.3	20.6	27.7	26	14.2	5.8	17.8
85.7	85.7	90.5	90.5	54.8	18.7	29.8	31.1	15.9	4.8	16.6
79.7	81	83.6	79.8	38	26.8	30.6	28	13	6.1	11.2
80.6	83.9	84.9	87.1	43	17	28.7	21.6	12.8	8.6	16.8
81.5	83.6	84.6	86.6	77.4	20.2	25.7	17.8	8.3	4.6	21.1
81.2	84.3	83.3	76	72.8	16.2	21	24.1	13.6	4.7	23.4
82.8	82.8	81.9	80	75.2	14.3	21	23.2	12.8	2.6	17.6
81.2	84.3	83.3	76	72.8	16.2	21	24.1	13.6	4.7	23.4
87.6	87.6	87.6	87.6	62.9	15.8	24	28	17.8	8	8
84	83	84	83	53.7	22.6	20.9	24.4	10.4	3.9	24.6
78.7	82.3	91.4	79.6	56.6	27.7	31.3	23.6	10.8	4.3	18.5
76.4	83.6	84.5	81.8	57.3	25.6	27.5	25.7	15.5	6.8	19.6
84.9	84.9	84.9	78.3	26.4	20.4	35.2	30.3	14.4	7	12.7
83.9	83	84	84	24.5	24.7	28.9	34.6	22.3	7.4	13.3
83	84.2	84.9	81.6	53.3	20.6	27.7	26	14.2	5.8	17.8
84.7	83.1	78.5	69.1	43.1	21.7	40.7	25.3	10.4	4.2	16.1
86.8	88.8	89.8	86.8	66.4	26.9	26.2	24.8	12.9	4.9	19.6
84.8	84.8	84.8	84.8	46.6	17.3	27.1	32.6	16.2	6.2	22.1
82.2	85.1	85.1	83.7	53.1	12.4	32.5	24.4	16.2	7.7	5.6

12ftiMH1	12ftiMH2	12ftiMH3	12ftiMH4	12ftiMH5	12ftiHx	18ppMH1	18ppMH2	18ppMH3	18ppMH4	18ppMH5
8.5	10.1	8.3	3.8	0.9	7	20.3	27.2	25.3	17.7	6.7
8.9	8.8	7.1	2.9	0.7	6.4	20.5	28	25.5	17.3	7.2
2.7	6.7	9.1	7.8	3.7	0.7	16.8	45.5	53.7	55.7	41.2
7.1	11	10.9	6	2	0.9	24.4	48.4	40.5	28.6	16.3
6.3	9	9	5.1	1.8	3	73.8	45.7	52.3	49.8	24.7
4.9	8.5	10.1	5.9	1.7	3.2	24.4	48.4	40.5	28.6	16.3
8	10.8	10.9	5.5	1.9	1.9	24.4	48.4	40.5	28.6	16.3
3.9	6.8	6.3	3.7	2.5	2.3	18.5	39.8	27.3	13.2	14.3
6	7.7	5.7	2.9	1.7	4.8	18	33.2	25.3	17	21.8
4.8	6.5	8.2	4.8	1.3	4.5	32.5	72.7	46	31.2	16.2
4.2	7	7.2	3.8	0.7	4.3	21	56.7	47.5	41.3	13.7
4.8	6.5	8.2	4.8	1.3	4.5	15.2	28.8	26.5	24.7	12.3
5.1	8.1	10.4	7.2	2.8	1.9	15.2	41	34	29.7	17.5
7.9	8.1	9.5	4.3	1.2	3.1	26.7	42.3	46	28	9.2
8.7	11.2	8.8	4.4	1.3	4.1	22.3	67.8	48.3	24	16.3
7.4	8.7	9.1	6.3	2.5	2.5	18.2	39.8	42.6	35.2	21.8
6.2	10.9	10.8	6.2	2.1	0.7	26.2	53.8	48.2	31	15.2
7.9	9.4	10.6	6.6	2	0.8	23.5	38.8	41.7	36.7	23
6.3	9	9	5.1	1.8	3	24.4	48.4	40.5	28.6	16.3
5.3	11.7	8.1	3	1	2.4	21.2	77.3	46.5	18.8	7.5
9.2	9.1	9	5	1.3	3.5	30.3	41	36.2	19	8
5.1	8.5	10.9	6	1.8	3	22.2	45.8	42.8	25.7	13.5
4.9	12.2	10	6.9	3.1	1.2	21.7	95.3	54.2	26.5	19

18ppHx	18ptiMH1	18ptiMH2	18ptiMH3	18ptiMH4	18ptiMH5	18ptiHx	18ctMH1	18ctMH2	18ctMH3	18ctMH4
70	7.8	10.5	10	7.1	2.7	17.8	75.4	79.6	78.8	78
42	2	7.7	9.6	9.1	6.7	2.7	77	79.6	80.5	82.3
28	6.3	16.2	17.1	17.8	13.9	2.9	82.7	86.2	87.9	87.9
51.4	7.2	13.2	12.4	9.9	6	7.9	76.9	81.6	82.9	83
51.2	20.8	15.6	21.2	24.2	10.6	4.7	86.3	87.1	87.1	86.2
51.4	7.2	13.2	12.4	9.9	6	7.9	76.9	81.6	82.9	83
51.4	7.2	13.2	12.4	9.9	6	7.9	76.9	81.6	82.9	83
33.3	4.7	8.7	6.9	4.1	4.5	4.9	70.4	77.6	79.6	80.6
19.5	4.4	7.3	6.5	5.4	6	3.4	78.3	81.4	84.5	87.7
29.8	7.2	16.2	13.1	9.8	6	3.2	75.9	82.1	83.9	84.8
105.8	6.3	12.6	11.7	10.2	3.1	22.2	78.6	80.6	82.7	81.6
56.3	4.7	8.4	10.2	8.9	4	13.5	77	81.2	84.3	83.3
56	5.1	11.5	11.7	10.6	6.9	9.4	79	87.6	87.6	87.6
112.8	9.7	13.5	14.3	10	4.2	14.2	76.5	81.7	84.3	85.2
40.2	6.4	16.2	13.5	8.8	5.7	6.5	72.3	77.2	81.2	82.2
29.5	4.9	10.4	12.3	10.8	8.2	4.4	71.6	75.6	80.4	81.4
49.7	7.5	13.7	13.1	9.9	5.3	3.5	80.4	82.4	84.3	84.3
60.3	6.4	10.2	11.4	10.9	8.3	5.2	78.8	81.7	84.6	85.6
51.4	7.2	13.2	12.4	9.9	6	7.9	76.9	81.6	82.9	83
51.5	6.2	16.3	11.8	5.7	2.3	7.6	71.9	78.1	81.2	74
60.2	10	12.7	11.8	7.1	2.5	9.4	71.8	85.5	76.7	74.4
55.3	6.8	13	12.4	8.4	5.1	7.4	73.8	78.7	79.6	83.5
24.3	9.4	31	17.3	9.8	7.5	6.7	83.6	85.8	86.5	87.3

18ctMH5	18ctHx	18mfMH1	18mfMH2	18mfMH3	18mfMH4	18mfMH5	18mfHx	18ftiMH1	18ftiMH2	18ftiMH3
76.3	74.5	19.8	24.9	21.6	10.6	3.1	39.1	7.1	9	8
80.5	67.3	5.5	22.7	23.3	20	9	2.8	7.9	8.6	7.8
87.9	45.2	10.5	18.9	24.4	22.4	13.3	6.2	3.5	7.5	9.2
80.2	54.5	18	27	25.5	16.1	6.8	20.6	5.6	8.4	8.8
78.2	31.4	28.9	20	26.2	23	4.8	16.3	9.7	7.3	10.5
80.2	54.5	18	27	25.5	16.1	6.8	20.6	5.6	8.4	8.8
80.2	54.5	18	27	25.5	16.1	6.8	20.6	5.6	8.4	8.8
83.7	49	21.3	30.2	20.4	10.8	6.5	28.6	5.2	7.8	6.3
87.7	61.8	15.3	29.3	23.6	13.6	9.7	18.4	3.8	7.5	7
83	44.7	18.7	38.3	30.7	17.7	8.1	18.1	4	9.9	9.8
79.6	81.7	15.9	22.2	25.2	14.1	2.5	18.4	4	6.7	7.1
76	72.8	16.2	21	24.1	13.6	4.7	23.4	4.8	6.5	8.2
87.6	62.9	15.8	24	28	17.8	8	8	5.1	8.1	10.4
83.5	47.8	24.6	23.2	26.8	11.7	4.1	23.8	8.5	8.9	10.4
78.2	43.6	14.6	32.4	24.7	17.2	6.9	20.1	4	9.5	8.7
80.4	55.9	13.1	21.3	26.8	20.9	8.5	18.6	3.5	5.8	8.4
78.4	35.4	20.9	32.8	29.1	14.2	6.5	23.5	5.6	9.6	9.7
85.6	38.5	18.6	26.8	30.3	19.8	8	25.1	5.1	7.6	10.1
80.2	54.5	18	27	25.5	16.1	6.8	20.6	5.6	8.4	8.8
61.5	49	19.8	34.5	22.3	10.8	5	21.5	4.7	9.1	6.8
68.1	62.4	31.3	31.2	22.9	12.4	4.4	32.6	10.3	10.8	8.7
82.5	53.4	16.1	30	31.5	17.6	7.6	39.8	4.7	9.2	10.3
85.1	57.5	14.6	30.6	22.9	17.1	8.5	8	5.4	11.3	9.1

18ftiMH4	18ftiMH5	18ftiHx	24ROM	24df	24pf	24ppMH1	24ppMH2	24ppMH3	24ppMH4	24ppMH5
3.8	0.9	9.1	110	80	30	22.5	26.2	23	15.3	6
3.6	0.9	5.4	105	90	15	18.8	24.2	21.8	16.3	6.7
8.2	4.1	0.6	40	40	0	18	51.2	62.5	58.2	40
5.5	2	3.5	60	50	10	30.5	41.2	43.7	31.7	18.3
9.9	2	1.5	50	55	-5	78	53.5	67	55.5	29
5.5	2	3.5	65	55	10	22.2	35.2	32.2	25.5	9.3
5.5	2	3.5	35	55	-20	56	42.5	41.2	24.7	7.8
2.8	1.8	4.3	95	75	20	16.3	41.5	29.7	15.3	17.5
4.4	2.8	3	95	75	20	17.3	30.8	21.5	13.8	17.3
5.9	2.5	1.8	100	75	25	29.7	55.5	44	28.5	12
3.8	0.6	4.3	80	60	20	22	51.2	52	44.3	15
4.8	1.3	4.5	70	60	10	10.8	35.8	31.5	31.2	16.2
7.2	2.8	1.9	70	60	10	22.7	46.7	32.3	26.5	12.7
5	1.5	3.1	55	50	5	29	39.8	44.2	25.2	9.5
5.8	2	3	75	60	15	26.7	68.2	53.2	22.8	14.3
7.3	3.1	2.3	55	50	5	27.5	38	41	29.7	15.2
5.5	1.9	2	30	35	-5	26.7	51	46.3	35.5	15.3
7.7	2.9	2.4	30	35	-5	27.2	40.5	44.2	33	16.5
5.5	2	3.5	60	65	-5	49.2	50.7	49.8	37	34
3	1.1	3.6	70	70	0	27.7	76.7	40.2	16.2	6.7
4.3	1.1	6.5	70	70	0	27.3	44.3	41	23.2	8.7
5.5	2.1	5.9	75	65	10	22.5	42.5	38.7	22.5	10.7
6.9	3.2	1.9	80	70	10	22.3	88.3	54.8	21.2	13.7

24ppHx	24ptiMH1	24ptiMH2	24ptiMH3	24ptiMH4	24ptiMH5	24ptiHx	24ctMH1	24ctMH2	24ctMH3	24ctMH4
79.8	7.7	9.4	8.6	5.9	2.4	20.3	73.2	76.9	76.8	75.9
47.8	6.2	8.1	7.7	6.2	2.7	8.3	73.9	78.4	80.2	81.1
31.5	6.3	16.7	18.4	18.4	13.3	3	83	88.9	88.9	88
27.7	8.4	12.4	13.1	10.3	6.3	4.7	79.5	83.7	82.9	83.7
53.7	25.3	16.1	21.5	23.1	10.1	5.5	85.5	84.6	88	86.3
70	6	9.6	9.7	8.5	4	8.3	73.1	79.6	82.4	85.2
22	15.1	12	11.4	8	3.2	3.7	77.4	80.8	82.6	80
23.7	4.4	8.6	7	4.4	4.6	4.1	78.7	81.9	83	83
26.3	4.3	6.9	6	4.8	5.9	4.8	80.7	83	85.3	88.7
28.5	8.9	14.9	13.1	9.4	4.4	5.4	80.7	83.5	85.3	81.7
57.7	7.1	14.2	14.3	12.2	4.1	11.5	79.8	82.8	83.7	83.6
38.7	3.6	9.5	11.4	10.9	5.2	9.7	76.2	82.2	85.1	85.1
70.3	6.3	11.6	11	9.6	4.9	9.3	78.6	83.5	84.5	85.5
109.2	9.9	12.9	13.7	9.3	4.1	16.4	76.1	83.1	84.9	84.9
49.3	9.1	18.3	15.2	8.4	5.7	11.7	73.2	78.6	83.9	82.1
41.7	8.6	11.2	12.2	10.1	6.4	7.5	69.6	76.6	82.6	83.5
31.3	7.2	12.4	11.8	10.1	5.6	2.5	78.3	83.2	84.2	84.2
94.3	7.8	10.2	10.8	8.8	5.4	7.1	75.5	82.7	82.7	83.7
17.2	19.4	16.2	15.7	12.9	12.8	2.6	83.4	89.5	86.6	83.4
78.3	8.2	16.2	10.6	4.9	1.8	11.4	71.3	76.6	79.8	72.4
42.2	10.1	14	13.2	8.5	3.1	6.9	85.9	85.9	86.9	87.9
77.7	7.8	13.7	12.3	8.5	4.2	11.2	78	79.8	79.8	84.4
37.7	9.2	29.3	17.2	8.5	6.1	9.1	81.8	85.2	86.8	85.2

24ctMH5	24ctHx	24mfMH1	24mfMH2	24mfMH3	24mfMH4	24mfMH5	24mfHx	24ftiMH1	24ftiMH2	24ftiMH3
75.9	76.8	21.3	24.1	20.4	9.6	3	40.7	7.4	8.1	7.1
80.2	55	21.8	22.9	19.6	10.3	3.4	33.9	6.3	7.4	7
88	36.1	10.5	20.1	26.2	23.3	12.3	6.9	2.9	7.3	9.4
78.6	67.4	19.5	31	32.3	19.3	7.4	17.2	4.3	9.1	10.4
78.6	37.6	29.2	19.9	28.8	23.6	5	19.4	10.3	6.9	9.9
84.3	56.5	15.9	26.7	27.9	14.8	4.5	16.8	4	7.7	9.2
80	40.1	36.2	32.1	31.6	11.5	4	13.2	10.6	10.5	10.2
86.2	59.4	19.7	31.6	23.4	9.9	5.8	21.4	5	8.2	7.1
88.7	66.3	18.7	28.8	20.3	12.1	9.2	23.8	4.4	7.6	6.6
76.2	56.1	24.7	32.9	28	15	5.2	15.6	6.5	10	9.4
79.9	78	12.4	24	28.6	16.2	3.8	11.3	3.4	7.9	9
80.2	70.2	11.9	20.4	25.9	16.9	6.6	20	3.6	6.6	8.8
81.6	55.3	20.2	25.6	26	14.3	6	14.1	5.7	8	9.2
83.2	55.8	26.8	23	25.4	11.5	3.9	23.9	8.8	8.5	9.8
82.1	62.4	21.6	30.6	24.1	12.9	5.7	19.7	7.1	10.5	8.8
80.8	61.7	26.3	24.4	24	15.7	5.9	20.6	7.6	7.6	8.2
77.2	38.7	19.9	32	31.1	16	6.2	17.4	5.2	9.1	9.9
82.7	41.8	26.4	29.2	31.1	17.9	6.2	27.2	7	8.1	9.1
76.7	51.1	28.8	23.8	23.8	14.7	9.3	8.4	11.5	10.2	9.4
56.4	56.3	22.9	30.6	18.7	9.5	4.7	28.1	6.2	8.5	5.7
86.9	70.8	7.9	24.9	24.3	12.3	4.3	22.7	10.5	9.3	9.4
80.7	61.5	21.8	32.6	22.3	13	4.8	41	6.5	10.9	8.2
83.7	64.3	17.5	31.5	21.8	14.2	7	10.6	6.6	11.8	8.8

24ftiMH4	24ftiMH5	24ftiHx
3.2	0.9	9.6
3.8	1.1	5.6
8.2	3.9	0.6
6.8	2.5	2.1
9.1	1.7	1.8
5.8	1.7	2.7
4.3	1.2	2.3
2.8	1.7	3.5
3.9	2.5	4.3
5.2	1.8	3
4.9	1.2	2.6
6	1.9	4
5.6	2	2.3
4.6	1.4	3.5
5	1.9	4.4
6.2	2.2	3.5
5.8	1.8	1.6
5.8	1.9	2.5
6.5	3.6	1.2
2.6	1	4.9
4.9	1.3	4.2
4.6	1.4	7.1
5.9	2.6	2.5

pp = peak pressure, pti = pressure-time-integral, ct = contact time, mf = maximum force, fti = force-time-integral
MH1 = 1st metatarsal head, MH2 = 2nd metatarsal head, etc, Hx = hallux.

APPENDIX I

RAW DATA OF RANGE OF MOTION OF FIRST METATARSOPHALANGEAL JOINT OF CONTROL SUBJECTS USED TO ASSESS INTRA-RATER RELIABILITY OF MEASUREMENT

Subject	Dorsiflexion	Plantarflexion
1.1	44°	10°
1.2	43°	10°
1.3	42°	9°
2.1	50°	10°
2.2	52°	9°
2.3	50°	12°
3.1	64°	15°
3.2	65°	16°
3.3	66°	14°
4.1	62°	10°
4.2	60°	14°
4.3	59°	16°
5.1	70°	30°
5.2	65°	22°
5.3	65°	22°
6.1	60°	20°
6.2	65°	20°
6.3	66°	18°

APPENDIX J

RAW DATA OF RANGE OF MOTION OF FIRST METATARSOPHALANGEAL JOINT OF HALLUX LIMITUS SUBJECTS PRE- AND 24-MONTHS POST-OPERATION

Subject	ROM 0m	ROM 24m	PF 0m	PF 24m	DF 0m	D 2
1	70	110	25	30	45	
2	80	105	30	15	50	
3	15	40	0	0	15	4
4	20	60	8	10	12	
5	32	50	0	-5	32	
6	60	65	30	10	30	
7	45	35	15	-20	30	
8	45	95	15	20	35	
9	45	95	15	20	35	
10	50	100	15	25	35	
11	40	80	10	20	30	
12	50	70	10	10	40	
13	32	70	8	10	25	
14	14	55	2	5	12	
15	35	75	10	15	25	
16	45	55	10	5	35	
17	25	30	5	-5	20	
18	24	30	6	-5	18	
19	37	60	2	-5	35	
20	40	70	0	0	40	
21	55	70	15	0	40	
22	40	75	10	10	30	
23	48	80	8	10	40	-

ROM = total range of motion°, PF = plantarflexion°, DF = dorsiflexion°

APPENDIX K

HALLUX VALGUS GROUP MEAN RAW DATA

Subject	Gender	Age	BMI	0ROM	0df	0pf	0ppMH1	0ppMH2	0ppMH3	0ppMH4
1	f	43	25.06	100	90	10	30.83	51.17	41.83	299.67
2	f	43	25.06	78	70	8	46.83	69.5	52.83	28.17
3	f	56	24.72	76	56	20	36.17	76	60.33	24.83
4	f	49	22.81	85	70	15	30.33	29.33	28.83	15.5
5	f	35	24.74	80	60	20	61	104	48.83	22.67
6	f	35	24.74	80	60	20	87.5	51.33	36.83	20.5
7	f	45	22.54	85	65	20	22.17	109.83	54	22.33
8	m	60	37.85	60	65	-5	64	75	68.75	31
9	f	47	31.88	70	50	20	16	66.83	70	31.33
10	f	44	22.01	95	70	25	60.5	49	42.33	23.5
11	f	44	22.01	90	70	20	39.17	61.67	53.5	26.5
12	f	53	21.77	94	66	28	106.17	91.33	60.5	36.5
13	f	53	21.77	90	80	10	91	70.67	54.67	30.17
14	f	68	25.95	65	55	10	19.83	11.5	35.83	37
15	f	68	23.59	65	65	10	23.17	39.83	43	35
16	f	68	23.59	70	60	10	19.83	44.5	41.17	52.33
17	f	55	24.82	55	45	10	14.67	43	59.83	75.5
18	f	14	17.1	85	65	20	18	96	25	27.5
19	f	55	23.34	80	70	10	37.5	43.67	41.83	21.33
20	m	45	41.37	80	70	10	28.2	71.7	56.7	75.3
21	f	53	29.43	65	45	20	24.25	80	74	29.25
22	f	37	21.37	105	80	25	36.33	23.33	22	17.17
23	f	37	21.37	90	70	20	37.83	27.83	27.5	17.17
24	f	55	22.59	62	56	6	18.83	42.17	43.33	40.67
25	f	51	27.66	96	84	12	80.67	79.67	54.33	29
26	f	51	27.66	90	90	0	68.83	56.83	41	19.67
27	f	61	30.55	85	65	20	35.67	30.67	33.33	21.33
28	f	69	30.3	78	70	8	18.33	69.33	53.83	27.67
29	f	69	30.3	76	70	6	14.67	52.17	45.83	27
30	f	62	23.83	67	65	2	46.25	77.5	57.5	20.75
31	f	62	23.83	68	64	4	59.83	85.47	64	29.17
32	f	74	29.91	75	65	10	74.83	73.67	64.33	25.5
33	f	74	29.91	75	65	10	48.17	75.5	45.33	23.67
34	f	41	23.74	80	70	10	58.5	61	42.83	28
35	f	41	23.74	70	60	10	35.5	63	70.33	27.5
36	m	42	32.03	61	55	6	25.67	42.5	40.17	45.17
37	f	54	25.22	80	70	10	53.17	102	82.17	39.83
38	f	37	22.04	70	60	10	26	82.67	32	17.83
39	f	37	22.04	75	70	5	66.67	39	18.5	11.33
40	f	51	26.56	75	65	10	80	78.17	41	23.17
41	m	56	24.34	60	70	-10	29.33	102.33	45.83	15.83
42	f	49	32.47	70	60	10	52.83	28.5	29	18.83
43	f	54	31.89	62	50	12	27.17	75	53.67	24.33
44	f	54	31.89	57	45	12	20	33.83	33.17	27.33

0ppMH5	0ppHx	0ptiMH1	0ptiMH2	0ptiMH3	0ptiMH4	0ptiMH5	0ptiHx	0ctMH1	0ctMH2	0ctHM3
21.33	81.5	10.59	16.11	13.71	9	6.84	23.99	84.23	88.88	87.96
18.33	102.17	12.62	18.19	15.02	8.83	5.78	22.34	81.67	86.28	87.16
28.5	78.5	12.37	23.61	17.24	7.97	7.71	23.59	85.85	87.6	89.38
11.5	60.5	9.32	9.78	9.85	6.56	4.88	17.47	76.7	79.29	83.63
17.17	109.67	14.64	29.69	14.93	8.22	5.51	32.78	79.81	86.84	87.76
23.17	124.67	21.37	12.71	10.45	6.64	7.47	34.51	77.4	82.62	85.23
26	65	6.91	6.01	5.11	4.28	5.81	11.56	85.37	92.3	92.3
24.25	29.5	22.9	20.65	19.37	12.43	9.98	6.6	88.01	86.79	89.2
32.17	58	5.14	18.54	20	10.7	9.57	21.17	75.58	85.72	88.25
12.5	33.83	10.67	11.75	11.3	70.02	4.19	4.58	80.01	80.93	85.46
16.5	37.17	6.48	7.65	6.79	6.79	6.79	6.61	76.28	83.93	83.95
109.17	75.5	34.6	26.93	19.27	12.58	36.23	17.95	87.56	87.4	86
19.5	35.33	29.71	23.46	19.13	12.12	7.59	10.31	87.66	86.94	87.66
26	71.83	7.45	9.71	18.72	16.73	9.4	21.46	82.59	84.97	91.3
14.67	65.33	7.87	13.01	13.92	12.25	5.41	14.84	81.74	85.06	87.54
12.33	89	5.99	13.55	14.8	15.98	5.73	19.03	73.4	81.46	85.48
47.33	58.17	4.74	13.6	16.99	19.37	15.56	14.9	78.17	89.13	89.13
32.83	44.33	5.41	23.51	7.34	7.42	8.38	11.16	80.37	85.99	84.08
10.5	89.83	12.6	13.08	12.91	7.3	3.82	20.27	82.59	83.34	83.39
26.5	67.7	12.9	27.1	24.8	27.3	12.7	25.4	88	90.4	90.4
30.75	40.5	6.6	23	22.63	10.92	7.57	13.13	78.56	84.72	86.2
8.33	35.67	9.87	7.96	7.71	6.07	2.61	9.37	85.43	85.43	82.55
8.83	30.67	9.7	8.42	8.53	5.63	3.37	5.74	83.17	84.12	86.05
30.5	37.5	6.09	13.41	14.91	13.3	8.56	9.59	86.93	87.81	89.56
15.67	51.5	25.96	22.91	17.77	11.01	4.88	12.48	80.44	82.88	83.71
12.17	83.33	26.39	17.38	14.12	8.01	3.63	23.84	81.89	84.5	86.21
15.5	86	12.28	8.72	8.89	5.33	3.83	27.42	78.77	79.65	80.6
20.17	45	6.33	19.66	15.72	8.76	6.56	14.19	85.54	89.17	90.1
27.33	65.33	5.89	18.31	16.41	10.14	10.05	16.67	91.26	93.8	92.92
13.25	65.25	14.35	24.75	18.64	8.73	6.32	23.88	78.71	82.49	84.99
23.67	75.5	18.71	21.98	20.06	10.85	8.18	20.36	80.14	85.47	88.04
22.83	39	19.01	20.77	17.54	8.74	7.69	8.02	82.34	86.53	87.39
22.5	50	14.33	24.37	14.92	9.25	8.68	16.93	82.17	88.71	87.06
7	62.17	14.3	19.75	15.35	9.87	2.81	19.91	82.64	86.1	86.95
7.67	60.5	11.12	17.82	21.54	10.48	3.1	21.11	80.78	85.55	86.43
69.83	62.83	7.24	12.27	12.95	19.27	26.2	12.6	80.93	84.26	86.76
43.5	60.17	16.4	34.72	26.86	16.37	15.11	14.98	72.44	81.15	83.5
16	48	8.06	19.51	9.44	5.89	5.06	9.2	84.02	86.99	86.01
11	59.17	19.86	9.74	6.35	4.1	3.73	13.54	84.28	84.28	83.27
12.17	119.33	28.14	20.55	13.62	9.41	5.07	41.81	79.99	83.33	85.81
7.33	45.17	11.83	39.92	15.3	6.62	3.65	25.28	81.48	81.48	81.48
12.83	42.17	14.28	6.72	6.98	6.17	4.15	10.2	94.44	88.89	94.44
18.67	76.33	8.85	22	17.96	10.32	8.43	7.9	82.25	86.9	86.9
27.33	86	7.32	10.94	10.66	8.47	7.58	13.86	78.11	82.01	83.58

OctMH4	OctMH5	OctHx	OmfMH1	OmfMH2	OmfMH3	OmfMH4	OmfMH5	OmfHx	OftiMH1	OftiMH2
87	85.13	86.13	12.99	28.91	23.18	15.98	12.81	26.82	4.73	10.08
87.18	84.43	83.47	22.06	35.03	35.68	19	9.1	15.94	6.44	11.09
87.62	88.5	90.3	14.29	32.44	29.61	14.54	9.44	15.46	5.44	11.14
87.06	86.22	80.84	27.35	22.84	22.54	12.2	7.03	24.46	8.89	8.46
88.62	87.71	86.84	25.62	39.36	24.63	9.79	5.27	22.66	7.16	13.21
86.11	86.11	86.11	31.47	28.62	20.6	8.7	5.67	30.76	8.52	9.03
22.33	81	63.55	18.67	42.43	35.75	16.05	8.46	10.42	5.52	14.47
89.2	83.16	59	26.63	24.17	26.77	17.38	9.58	11.06	9.63	9.16
89.98	87.46	81.46	10.49	22.34	32.86	20.65	9.97	10.98	3.1	7.93
84.56	81.86	71	31.23	25.12	37.75	18.01	7.18	10.24	6.45	7.05
83.93	83.95	61.65	22.44	32.29	40.15	19.59	10.28	12.29	3.83	8.69
89.94	88.33	85.11	20.87	23.73	22.5	14.56	17.59	8.33	7.77	8.69
90.01	85.39	87.66	30.26	23.79	25.22	15.98	8.16	6	11.5	9.36
89.78	81.08	80.39	19.87	22.05	30.39	23.81	8.56	23.9	6.78	9.71
86.72	83.43	80.89	27.04	28.15	30.91	18.35	4.54	15.94	8.16	9.7
86.3	85.48	75.78	18.96	25.64	30.93	17.72	4.62	22.51	4.98	8.3
94.49	86.4	82.7	6.4	20.9	25.7	19.64	12.43	22.81	2.1	7.24
85.06	84.08	80.35	15.09	40.26	19.28	15.7	10.22	25.9	3.75	11.44
81.68	77.51	78.17	32.81	28.11	28.52	15.23	5.12	23.22	11.23	10.26
92	89.6	86.4	23.3	24.2	22.8	17.7	8	12	9.6	11.3
86.2	81.5	84.58	12.34	37.74	27.58	17.53	10.16	12.48	3.01	11.88
81.57	78.66	78.66	36.24	24.73	20.58	12.5	4.9	17.76	10.53	8.9
84.22	84.12	74.77	39.62	26.1	27.01	13.1	4.16	10.68	10.42	8.45
88.69	83.47	86.08	17.17	24.41	30.54	18.22	10.75	9.86	4.82	8
83.71	83.71	74.01	30.52	26.53	29.64	15.04	4.02	11.36	11.68	10.75
87.07	86.21	80.18	31.29	26.36	20.03	10.87	2.61	21.15	12.98	10.92
80.6	83.46	79.72	28.44	22.45	23.51	9.78	4.9	29.65	9.4	7.4
90.1	88.32	87.32	15.79	27.41	26.67	15.85	6.83	20.37	4.88	9.56
95.6	95.6	78.17	12.94	23.75	28.18	16.92	10.11	14.7	4.56	9.62
84.99	86.21	87.55	20.1	27.09	28.3	13.48	9.87	19.45	8.14	11.6
89.63	85.47	20.36	18.64	24.75	36.65	16.69	10.32	15.57	7.08	10.18
87.39	80.63	80.68	27.42	24.86	25.97	15.27	9.18	8.3	7.65	8.05
87.85	85.41	87.06	25.5	25.56	22.89	16.34	9.83	13.24	8.65	10.22
86.1	82.61	85.22	27.06	33.74	29.17	11.83	2.78	13.21	7.87	11.94
84.76	83.88	90.41	20.17	29.29	37.14	16.11	3.22	10.98	6.74	10.51
87.5	81.76	52.59	16.16	24.46	24.44	24.32	23.08	26.63	3.77	7.09
85.03	75.6	64.71	26.81	22.93	26.51	19.23	13.42	8.17	8.17	9.19
86.01	82	73.02	19.26	40.55	23.59	18.42	9.54	17.87	6.12	12.1
84.28	80.35	82.31	46.45	24.44	17.07	13.77	7.99	32.52	14.87	8.55
83.29	84.99	80.05	30.04	24.76	20.96	11.28	4.9	25.97	10.06	9.41
81.48	77.78	88.89	17.18	28.59	24.33	12.29	4.5	16.54	7.41	13.19
94.44	88.89	100	32.77	16.38	21.43	14.4	7.25	9.45	9.74	4.76
86.9	85.35	63.02	17.56	28.26	24.6	13.74	7.88	11.84	5.46	10.26
84.34	79.7	83.67	18.79	18.23	20.85	14.99	7.94	17.96	5.87	6.86

0ftiMH3	0ftiMH4	0ftiMH5	0ftiHx	3ppMH1	3ppMH2	3ppMH3	3ppMH4	3ppMH5	3ppHx	3ptiMH1
8.47	5.85	4.13	6.85	42	73.33	50.17	29.67	16.17	30.83	11.84
11.24	6.33	2.87	3.59	25.5	79.5	57.33	29.67	16.33	39.5	8.41
9.97	5.03	2.8	5.17	22.33	70.17	64.33	25.17	26.33	50.67	8.69
9.01	4.84	2.43	7.24	29	31.33	31.17	19	8.67	43.33	11.11
9.56	4.45	2.26	6.68	25.25	106	44.25	34.75	26.5	4	8.32
7.34	4.06	2.63	7.52	74.5	72.33	50	23.83	26.67	34.83	19.66
11.84	4.96	2.06	2.14	28.83	77.83	33.5	15.67	13.33	31.33	9.57
9.91	6.98	3.73	2.28	29.05	58.04	47.94	31.55	25.54	29.7	12.56
11.54	7.59	3.29	3.38	21.5	83.83	72.17	31.5	35.33	18	7.84
10.98	5.48	2.33	1.74	34.33	41	39.5	23.83	14.33	41.83	8.66
12.91	7.37	3.62	2.17	21.17	29.56	33.35	29	14.5	39.83	6.13
8.71	6.54	6.96	2.26	29.05	58.04	47.94	31.55	25.54	29.7	12.56
10.21	7.38	3.3	1.99	29.05	58.04	47.94	31.55	25.54	29.7	12.56
14.84	10.31	2.76	6.6	29.05	58.04	47.94	31.55	25.54	29.7	12.56
11.43	7.05	1.88	4.31	13.33	32.17	36.5	46.33	62.83	6.5	85.69
11.82	7.42	2.31	5.7	35	67.5	55.25	66.5	17.5	9.25	8.49
10.31	8.71	4.18	6.4	19.83	51.33	55.5	52.83	37.83	12.83	8.22
6.39	5.48	3.23	5.83	29.05	58.04	47.94	31.55	25.54	29.7	12.56
10.25	5.21	1.55	5.88	29.05	58.04	47.94	31.55	25.54	29.7	12.56
11	8.3	3.8	5.1	29.05	58.04	47.94	31.55	25.54	29.7	12.56
10.96	5.67	2.27	3.79	40.33	76	92.33	37.83	38.17	32.5	13.67
7.39	4.03	1.17	4.44	13.5	34.5	37	47	23.5	9	6.02
8.85	4.47	1.38	2.31	36	30	28.75	15.25	82.24	29	11.49
11.17	7.38	3.89	2.56	19.33	36.83	50.67	50.5	37.17	27.5	8.24
12.61	5.91	1.51	3.34	65.5	84.36	57.17	35.83	11	24.33	20.92
9.27	4.36	0.93	6.72	63.5	80.67	51.17	26.33	11.17	31.83	21.79
7.15	3.2	1.6	8.9	36.17	36	35.17	20.33	17.67	46.67	12.08
9.71	6.42	2.59	5.63	19.33	77.17	57.83	40.33	33.83	15.17	7.35
11.13	6.86	3.65	3.69	15.33	62.67	64.83	27	26.67	78.33	6.26
11.81	6.12	3.28	7	29.05	58.04	47.94	31.55	25.54	29.7	12.56
13.79	7.7	3.53	5.69	29.05	58.04	47.94	31.55	25.54	29.7	12.56
9.03	6.06	3.41	2.24	29.05	58.04	47.94	31.55	25.54	29.7	12.56
9.28	7.13	3.76	4.85	29.05	58.04	47.94	31.55	25.54	29.7	12.56
11.13	4.44	0.91	4.09	19.83	56.5	59.5	33	19.83	27.33	8.13
13.67	5.92	1.01	3.92	18.5	48.33	67.17	25.33	11.33	44.17	7.58
8.31	10.04	8.51	5.07	29.05	58.04	47.94	31.55	25.54	29.7	12.56
10.62	8.51	4.65	2.5	34.5	58.5	40	41.75	23.75	28	12.1
7.83	6.02	2.83	3.31	15.5	75.17	27.5	19.5	14.17	23.67	5.48
5.65	4.01	1.94	7	26	54.33	34.83	14.17	8.67	14.33	9.44
8.39	4.51	1.76	8.51	29.05	58.04	47.94	31.55	25.54	29.7	12.56
10.98	5.91	2.13	8.03	29.05	58.04	47.94	31.55	25.54	29.7	12.56
6.04	4.88	2.35	2.39	14.83	37.17	36	24.67	17	18.5	5.9
10.22	6.02	3.15	1.93	21.17	42.83	41	28.83	21.5	35	9.14
7.25	4.83	2.2	3.77	19.83	34.33	34.33	31.17	52.17	42.83	8.66

3ptiMH2	3ptiMH3	3ptiMH4	3ptiMH5	3pitHx	3ctMH1	3ctMH2	3ctMH3	3ctMH4	3ctMH5	3ctHx
22.15	16.04	8.99	5.23	6.9	84.35	88.69	89.56	90.42	87.81	68.62
22.38	18.01	10.14	6.49	8.19	80.85	85.85	86.68	85.04	84.18	71.66
20.66	18.67	8.74	7.33	10.93	87.74	89.29	89.27	90.17	89.27	69.53
11.14	10.52	6.52	4.17	10.21	77.62	80.18	82.77	86.21	85.36	69.75
29.76	14.92	11.72	8.55	0.54	76.25	85	86.25	88.75	87.5	20
18.3	14.5	8.24	8.04	7.34	79.47	83.58	85.26	86.08	86.08	67.17
21.59	11.74	5.15	3.16	3.32	84.55	88.59	91.89	89.43	77.21	33.43
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
23.65	21.26	10.99	10.36	2.79	80.68	84.89	88.23	88.25	85.73	50.58
10.72	10.62	7.3	4.52	5.28	82.8	86.45	90.06	86.4	85.48	58.24
12.36	0.94	8.16	4.7	7.07	82	87.38	88.28	87.43	87.43	60.39
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
11.55	12.35	12.81	11.3	0.46	85.69	89.54	90.52	90.42	85.69	16.09
16.8	16.86	18.64	6.03	1.36	82.89	86.84	89.47	90.76	88.16	31.58
19.71	20.97	18.25	12.35	3.57	81.92	89.89	91.49	90.63	85.78	65.3
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
27.85	35.63	16.05	11.63	8.94	83.91	86.59	90.2	88.37	86.55	70.58
10.65	13.04	15.69	7.44	1.66	88.98	88.89	88.98	91.67	83.33	55.56
10.31	10.1	5.65	2.98	5.98	83.6	83.6	84.95	84.98	82.24	73.99
13.54	16.36	2.24	10.47	6.45	87.57	89.94	89.94	89.94	86.84	63.26
21.87	17.64	11.14	3.57	5.56	81.71	84.36	85.34	82.59	81.1	68.56
23.58	17	10.19	1.23	8.68	85.38	88.13	87.18	89.03	85.33	78.02
10.87	10.28	6.17	4.35	11.5	75.83	78.56	79.43	82.12	81.29	65.4
24.29	17.48	11.78	9.84	4.23	84.68	86.5	87.41	87.41	84.75	70.33
20.76	20.42	10.49	9.1	19.25	84.88	87.36	87.36	87.36	86.59	72.72
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
20.65	20.42	11.13	6.62	7.35	80.09	80.09	80.09	88.43	84.26	60.19
16.87	21.38	10.02	3.68	12.98	76.85	76.85	76.85	81.02	76.85	84.72
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
16.88	12.5	13.55	8.08	6.8	86.61	86.61	86.61	92.86	79.46	66.07
17.28	7.82	5.88	4.23	3.91	76.65	80.64	81.72	83.8	77.85	50.39
12.59	9.17	4.84	3.52	3.24	87.35	87.35	85.42	82.5	82.5	62.03
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
17.53	15.1	9.98	6.83	6.39	82.52	85.49	86.68	87.42	84.29	61.51
9.51	9.38	7.64	5.44	4.56	80.39	82.35	84.31	89.22	83.33	91.18
14.87	14.39	10.12	7.07	3.56	83.52	87.63	88.42	86.8	86.74	53.14
12.73	12.53	11.18	13.5	9.04	80.74	83.15	86.38	86.38	83.98	76.79

3mfMH1	3mfMH2	3mfMH3	3mfMH4	3mfMH5	3mfHx	3ftiMH1	3ftiMH2	3ftiMH3	3ftiMH4	3ftiMH5
21.79	40.53	34.1	17.47	5.86	12.43	6.81	14.28	12	8.99	2.26
21.31	40.19	37.37	18.46	7.95	8.88	6.82	14.16	13.44	7.32	3.12
20.62	31.36	32.53	13.88	7.21	14.83	7.61	11.47	11.82	5.36	2.58
34.91	28.08	23.77	11.08	6.1	18.87	12.27	11.02	9.5	4.63	2.05
14.35	47.59	29.63	19.73	9.07	1.36	4.57	15.01	11.5	8.09	3.58
24.44	36.8	28.74	13.01	7.92	8.54	7.24	11.73	10.28	5.61	3.18
22.39	35.26	26.3	13.77	5.76	5.22	7.18	11.95	8.82	4.09	1.34
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
16.35	30.89	36.09	19.64	10.02	3.93	5.06	10.89	12.61	7.27	3.5
32.51	28.48	32.17	16.64	7.18	16.33	8.13	8.31	9.71	5.43	2.38
23.58	29.56	33.35	18.75	8.43	17.03	5.69	9.1	9.99	5.74	2.51
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
9.47	18.85	27.62	27.27	18.94	2.4	3.03	7.68	9.35	7.78	4.01
13.58	36.01	39.99	21.18	7.18	4.88	3.2	9.95	12.93	7.29	2.06
14.73	27.46	31.64	21.76	9.22	7.34	5.47	12.02	14.01	9.57	3.75
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
13.76	32.84	32.43	18.7	11.79	9.95	4.59	13	15.42	7.49	3.27
16.59	26.34	31.29	21.83	10.7	3.57	6.33	9.36	12.11	8.34	3.33
37.56	29.42	25.46	11.17	4.01	9.33	12.12	10.68	9.22	4.14	1.24
15.73	24.55	32.06	23.85	12.67	6.6	6.26	9.48	12.57	9.35	4.39
28.69	28.11	31.26	15.34	3.73	6.59	10.36	10.79	12.02	5.8	1.27
27.83	31.7	25.65	12.85	3.77	11.28	10.36	12.25	11.04	5.21	1.23
30.84	28.44	25.6	11.77	5.37	19.7	9.85	9.23	8.13	3.79	1.6
15.83	29.03	30.33	20.86	10.18	9.62	5.26	11.03	10.79	7.51	3.36
14.74	23.64	29.89	16.46	9.12	22.18	84.88	9.76	11.87	6.8	3.45
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
15.82	35.01	31.69	12.52	5.56	4.49	6.04	14.29	13.03	5.43	2.12
16.3	30.92	30.91	14.07	4.09	7.99	6.18	12.04	12.17	5.27	1.34
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
25.67	20.96	21.78	19.86	7.75	9.05	8.85	7.06	7.86	6.79	2.95
15.83	31.43	22.18	17.8	8.5	14.93	5.11	9.66	7.13	5.46	2.32
30.63	30.94	20.08	11.61	6.11	10.38	10.9	10.12	7.19	4.47	1.92
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
20.97	29.92	29.26	17.13	8.16	9.97	9.69	10.69	10.78	6.4	2.65
16.36	21.99	25.42	18.03	10.11	9.31	5.81	7.1	8.36	6.57	3.18
19.27	22.65	26.31	16.97	8.14	9.44	7.89	9.11	9.65	5.86	2.46
17.71	18.51	22.26	18.07	12.26	12.72	6.8	8.25	9.05	6.74	3.71

3ftiHx	6ppMH1	6ppMH2	6ppMH3	6ppMH4	6ppMH5	6ppHx	6ptiMH1	6ptiMH2	6ptiMH3	6ptiMH4
2.77	50.67	81.17	55.83	26	18.17	59.17	13.14	25.38	17.83	8.91
1.87	25.83	93.33	74.33	28.5	13.17	65.17	10.27	28.67	22.9	10.56
3.79	46.5	67.17	52.67	19.33	17.17	107.17	13.8	21.87	17.62	7.72
4.59	25.83	27.6	31.33	19	18.17	39	8.66	10.24	10.05	7.53
0.21	41	120.25	50.75	26	20	12.75	11.91	34.62	15.54	9.05
2.02	102.33	71.5	42.33	18.83	21	85.83	23.85	17.24	12.12	6.65
0.62	33.67	110.5	51.33	20.33	18	66.17	11.87	30.96	16.22	6.38
2.13	52.17	88.83	77.83	34.33	28	15.83	21.65	25.37	23.93	14.54
0.66	17.5	91.5	74.83	34	32.83	34.33	6.88	26.17	22.87	11.71
2.71	32.83	35.5	33	21.67	15.33	57	7.68	9.95	9.65	6.78
2.96	32.67	52.38	45	23.67	11.5	46.5	8.3	14.21	13.09	7.58
2.13	124	91.83	55.5	37.17	99.67	88.33	47.17	26.91	18.87	14.71
2.13	17.5	65.17	53.17	27.67	22.17	60	39.35	22.79	21.05	12.43
2.13	13.33	42.5	80.33	71.83	31	29.67	4.61	15.94	25.29	24
0.14	19.33	41.83	46.83	41.33	23.17	5.67	5.57	13.11	14.55	12.87
1.36	24.67	68	50.5	48	12.83	16.33	6.88	17.21	16.15	16.28
1.99	18.83	58.17	59.5	17.47	22.17	77.17	6.88	18.52	19.36	16.45
2.13	32.83	83	38.67	58.5	88.67	13	9.81	19.69	9.84	12.67
2.13	31.88	47.33	47.17	23.67	9	33	13.21	15.05	14.3	7.58
2.13	38.67	92.5	96	100	41.17	10.67	21.5	43.63	41.7	37.88
2.85	40	99.67	70.17	26	20	71	13.96	32.7	26.59	10.77
0.65	19.33	40.33	32	33	15.17	16.5	5.51	9.37	9.32	10.05
0.65	49	29.33	28.67	15.83	8.33	29.17	11.91	9.25	9.08	5.25
1.6	55.5	35.33	33.33	27.33	18	73.83	17.12	10.33	10.45	8.85
1.8	62.67	90.67	50.17	30.67	8.5	27.33	21.57	25.9	16.66	10.63
3.12	74.5	79	36.67	21.67	7.83	41.17	25.38	20.89	13.5	8.79
4.01	38	45	43.75	24.75	12.5	18.75	12.21	12.08	11.59	6.55
2.52	33	53.5	49.83	26.17	16.17	18.5	10.88	17.32	15.09	7.57
5.47	11.83	45.5	45.17	28.17	26.5	68.5	4.47	15.02	14.73	10.26
2.13	19.5	43.67	36	19.17	11	29.17	8.67	13.41	11.11	6.65
2.13	18.5	47.17	35.5	24.17	37.33	43.5	7.65	15.21	11.3	8.93
2.13	44.83	61.5	53.33	27.83	19.5	12	13.74	17.66	15.39	8.75
2.13	32.83	59.5	41.5	25	33.17	10.83	12.27	17.7	13.39	9.39
1.3	28.5	47.33	38.83	22.17	9	36.33	10.96	19.78	17.01	9.82
2.2	20.33	45.17	57.33	28.5	15.67	39	8.08	18.7	22.75	13.21
2.13	21.67	38.33	35.83	30.33	56.33	52.83	6.05	10.13	9.65	11.33
2.1	36.66	64.39	49.47	29.32	22.95	42.53	12.94	18.91	15.94	10.52
2.37	30.83	107.17	38.33	17.83	10.83	23.5	7.6	18.72	7.89	4.42
2.15	23.5	72	40.17	17.5	11.67	17.17	7.04	14.89	10.34	5.4
2.13	56.5	92	41.67	26.83	16.67	57.33	16.44	21.19	13.68	9.95
2.13	20.67	68.67	66.17	13	6	37.83	9.43	12.73	21.57	5.82
1.89	43.67	38	37.17	17	10	33.17	12.53	8.51	8.06	5.77
0.96	27.5	64.17	64.17	29	14.83	86.67	11.37	21.27	20.77	10.72
2.7	21.83	35.67	34.5	31.5	38.67	62.17	8.48	12.91	12.53	11.11

6ptiMH5	6ptiHx	6ctMH1	6ctMH2	6ctMH3	6ctMH4	6ctMH5	6ctHx	6mfMH1	6mfMH2	6mfMH3
5.54	13.34	82.38	88.28	89.14	89.1	86.57	67.38	22.33	40.56	31.33
6.11	16.44	79.69	85.12	85.92	85.17	84.38	75.73	19.01	40.93	37.35
6.48	22.4	84.48	87.92	88.8	86.19	88.78	78.45	27.17	31.8	24.64
6.96	9.99	78.15	78.18	81.81	85.44	84.53	68.24	29.57	27.6	24.44
5.54	3.13	75.66	84.67	84.61	87.17	85.92	69.41	19.12	47.05	28.67
6.1	17.7	75.87	83.6	86.21	85.34	84.48	66.35	26.86	4.62	23.79
4.26	9.34	87.83	91.32	93.05	89.59	77.4	59.2	26.14	45.16	33.77
12.34	1.39	84.61	86.3	88.86	87.98	82.85	33.41	24.04	29.55	30.39
10.05	8.87	81.2	83.76	87.17	87.18	87.18	68.38	13.88	31.58	35.7
4.49	8.32	83.16	86.13	88.12	87.11	86.13	59.39	28.3	26.78	30.18
4.63	9.79	81.29	85.77	86.6	85.67	84.84	74.03	30.68	31.8	32.12
38.53	19.9	81.12	81.91	84.26	86.64	83.48	81.1	30.03	27.8	20.95
9.49	17.09	88.28	87.55	88.31	89.11	88.31	85.25	31.8	24.78	25.17
12.44	6.11	74.78	86.49	90.73	91.66	88.32	68.41	9.76	21.29	41.03
8.45	0.84	79.86	85.98	86.86	88.66	87.76	30.67	16.73	30.6	34.15
5.82	3.22	73.12	83.5	86.94	86.94	86.11	47.82	19.4	33.2	34.62
8.89	18.79	78.76	85.85	88.5	88.5	82.29	73.42	14.81	26.11	29.98
18.85	2.33	82.56	85.31	86.24	87.14	84.38	41.22	14.96	38.99	27.12
3.18	5.86	84.78	87.32	88.16	85.61	81.36	69.52	30.63	28.84	27.94
17.94	1.51	92.57	94.09	95.59	96.34	91.1	80.04	21.76	29.85	26.18
5.88	22.91	82.14	86.72	88.65	87.73	84.91	80.14	23.82	37.89	25.81
4.68	2.97	81.87	81.87	81.87	82.88	78.84	55.59	23.35	30.64	28.84
3.18	4.37	84.69	84.69	84.69	82.67	81.63	64.3	41.44	28.7	25.1
4.78	14.83	91.07	10.33	91.07	91.07	86.9	81.55	29.13	22.33	23.47
2.82	5.43	83.6	84.48	85.34	85.34	81.04	68.98	27.38	29.15	27.55
3.62	9.59	81.29	83.71	84.57	83.74	82.12	70.14	26.77	29.76	22.91
4.06	3.88	80.01	82.65	84	86.66	84	60.17	35.49	32.94	31.19
4.39	5.51	86.8	90.26	91.06	88.52	84.92	76.38	25.14	23.91	22.79
8.72	15.62	88.42	90.2	92	91.1	90.25	73.11	10.45	18.71	24.74
4.9	3.81	84.53	86.36	88.16	88.19	88.19	74.52	20.47	24.87	21.33
12.87	14.27	81.11	83.53	86.93	87.76	81.94	85.41	16.47	28	22.87
5.93	3.41	84.11	86.72	88.47	88.52	82.35	74.34	23.56	25.09	23.66
9.87	2.5	85.77	86.62	88.31	87.45	84.12	67.46	21.43	26.19	22.19
3.49	10.41	82.59	86.38	87.17	84.9	81.79	67.82	20.99	31.03	26.39
6.03	12.72	78.52	86.23	86.91	84.95	77.84	64.9	12.89	29.44	29.32
17.02	8.75	78.85	82.69	86.55	86.55	85.6	57.79	18.84	22.64	22.17
7.77	9.26	82.23	83.97	87.26	86.93	83.76	66.65	23.63	29.27	27.34
2.88	2.65	82.44	87.96	84.66	83.55	76.99	37.31	31.39	39.24	24.91
3.75	2.71	87.57	87.57	87.57	86.59	81.4	52.06	27.44	36.36	26.39
5.39	10.76	74.6	82.86	84.44	84.4	77.86	61.67	24.22	24.3	22.51
2.97	10.14	82.6	89.14	87.69	86.23	80.43	80.44	23.74	27.95	28.15
3.47	6.69	81.08	81.05	84.21	85.28	79.97	89.48	30.52	22.11	20.2
5.71	19.64	80.46	83.56	84.39	82.4	80.46	70.31	25.66	26.22	28.98
11.66	8.42	82.04	85.94	87.5	85.16	82.04	54.65	18.78	22.26	24.64

6mfMH4	6mfMH5	6mfHx	6ftiMH1	6ftiMH2	6ftiMH3	6ftiMH4	6ftiMH5	6ftiHx	12ppMH1	12ppMH2
15.26	5.36	20.95	6.9	15.49	11.94	5.99	2.13	4.49	41.5	90.5
15.4	6.55	13.68	7.3	16.08	14.63	6.83	2.95	3.49	28.8	88.3
10.55	5.8	29.17	9.17	11.7	10.21	4.29	2.1	7.31	39.2	59.8
13.42	9.71	19.78	9.34	9.57	9.19	5.27	3.18	4.89	20.2	28.2
12.25	5.53	6.38	11.91	15.03	10.79	4.89	2.24	1.36	69	120.5
10.54	5.62	20.14	6.98	10.54	8.17	4.09	2.12	4.22	106.2	74.2
15.47	6.31	13.07	8.5	15.12	11.05	4.63	1.59	2.04	38.5	111
19.46	10.7	4.09	9.07	11	11.29	8.37	4.43	0.37	72.5	66.5
17.88	9.29	6.8	4.9	11.73	13.18	6.97	3.24	1.97	22.3	75
15.98	7.36	21.66	7.03	7.73	8.97	4.97	2.3	3.95	26.7	39
14.05	5.97	23.66	7.38	10.36	10.66	5.27	2.38	4.44	33.8	40.8
12.14	15.96	14.06	11.96	9.97	8.32	5.82	6.46	3.79	35.04	59.91
15.75	8.74	12.46	12.52	10.14	11.18	7.59	3.85	3.51	35.04	59.91
30.65	9.84	16.36	3	7.76	15.4	12.12	3.93	3.49	13.17	28.83
22.41	9.12	2.54	4.1	9.52	11.64	7.78	3.32	0.34	26.17	43.67
17.48	4.62	10.18	4.5	9.88	12.45	7.14	1.93	1.73	19	66.3
17.47	7.61	16.65	4.35	10.08	11.91	7.24	2.69	4.39	19.8	77.8
27.17	20.02	9.48	3.75	9.93	7.89	8.09	5.46	1.4	35.04	59.91
12.25	3.86	20.87	12.11	11.02	9.81	4.17	1.18	3.78	37.5	38
20.88	9.08	4.13	9.93	15.22	14.07	10.82	4.72	1.51	35.04	59.91
13.12	7.09	15.77	8.1	14.42	11.6	4.82	1.78	5.35	35.04	59.91
19.46	8.51	8.61	5.83	8.56	9.22	6.12	2.3	1.49	31	35.3
10.74	4.49	12.49	11.27	9.34	8.26	3.75	1.49	2.15	35	27.3
13.07	5.99	16.74	9.44	7.55	8.2	4.76	1.95	3.38	74.3	28.8
12.84	2.89	6.92	10.15	11.08	10.89	5.06	1.02	1.61	34.2	66
11.18	3.91	11.79	10	11.05	9.86	4.85	1.44	3.04	51.5	54.8
14.55	5.67	11.1	10.74	10.05	9.4	4.62	1.76	1.92	41	32.7
13.03	6.25	11.48	8.01	8.9	7.73	4.16	1.63	5.51	25.3	90.2
15.97	8.81	19.47	3.26	7.15	9.33	6.21	3.11	4.32	16.2	48.7
12.09	11	14.65	8.62	9.53	8.04	4.84	2.72	3.81	25	47.7
14.43	11.07	16.71	6.79	10.51	8.87	6.3	4.14	5.76	22.5	47.5
11.61	6.64	5.06	7.64	8.58	8.03	4.57	2.33	1.13	35.04	59.91
15.87	9.99	4.91	7.94	9.76	8.65	6.63	3.81	1.04	35.04	59.91
10.61	2.86	9.92	7.85	13.74	12.29	4.68	1.01	2.75	35.04	59.91
15.23	4.91	7.54	4.72	12.77	13.97	7.05	1.94	2.37	35.04	59.91
16.69	15.14	17.47	4.8	6.32	6.54	5.92	4.95	3.07	16.8	43.5
15.2	7.6	13.45	7.85	10.58	10.13	5.84	2.65	3.01	32.2	88.8
14.32	6.27	14.96	7.24	9.07	6.27	3.84	1.59	1.59	31.5	71.2
16.52	8.04	11.75	8.07	10.46	8.5	5.31	2.39	1.76	25.3	59.2
13.48	5.48	15.55	7.39	8.52	8.31	4.84	1.61	3.01	70.2	90.2
8.69	3.22	16.57	10.18	13.58	12.37	4.47	1.57	4.26	14.7	70.7
12.32	6.64	12.31	9.27	6.53	6.16	4.26	1.95	2.26	18.3	38.7
12.48	4.56	13.99	9.36	11.08	11.43	5.16	1.86	3.04	24.8	66.3
18.77	10.06	16.62	6.36	8.51	9.15	6.76	3.26	2.55	22.3	41

12ppMH3	12ppMH4	12ppMH5	12ppHx	12ptiMH1	12ptiMH2	12ptiMH3	12ptiMH4	12ptiMH5	12ptiHx	12ctMH1
44.3	20.8	10.8	59.2	11.1	25.7	14.5	7.4	4	10.4	75
54.3	22.2	10.8	75.7	10.7	26.4	19	9.1	4.8	14.2	83.3
49.2	19	16	101.8	12.1	21.5	17.1	7.7	6.4	18.8	83.3
26.5	14.3	13.5	47.2	6.7	8.8	8.5	5.7	4.8	11.1	76.4
52.8	24.7	16.3	45.2	18.1	34.7	15.9	8.8	6.1	11.1	78.3
41.2	17.2	20.2	108.7	23.7	19.1	12.5	6	6.4	23.8	82.2
46	17.5	15.7	87.2	15.5	37.4	16.5	6.1	4.3	16.6	95.8
59.7	34.7	29.8	10.8	27.3	16.9	15.6	13	12	1.7	78.6
72.2	30.2	20.3	39.7	7.3	21.3	19.6	9.3	6.4	13.7	79.3
34.5	24.2	15	31.5	6	10.6	10.1	7.2	4.7	5.6	82.1
36.7	17.8	11.5	38.8	7.3	11.4	10.9	6.8	4.9	6.3	77.8
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
42.33	37.67	16.5	23.33	6.33	13.71	18.11	16.29	8.13	6.48	82.21
41	25.17	9.33	16.33	6.97	11.56	11.46	8.37	3.6	2.62	77.71
45.8	36.7	10.2	22.3	5.4	16.2	13.9	12.5	4.6	4.9	62.2
51.8	29.7	16.8	110.8	8	22.7	19.3	13.2	4.8	32.6	77.5
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
31	16.8	7	36	13.2	13.1	10.9	6.2	2.7	5.9	79.3
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
25.8	16.7	6.5	29.5	8.8	9	8.1	5.9	1.9	6.6	84.2
26.8	15.7	7.2	23.7	9	8.2	8	4.7	2.2	3.9	83.8
28.8	21.2	8.5	81.5	23.1	8.5	8.7	6.8	2.8	17.5	89.9
38	27.5	14.7	31.2	10.1	20.3	13.3	9.9	4.8	6	82.4
30.2	17	13.5	48.3	15.6	16.7	11.2	7.3	4.9	9.8	79.7
32.7	21.5	11	13.2	14.9	10	9.3	5.3	3.1	3	81
50.7	28.3	16.5	23.3	8.1	22.7	15.7	8.2	5.2	5.6	71.1
40.5	23.5	21.3	95.5	6	14.8	12.7	8.7	7.9	24.3	80.5
32.3	16.3	11.8	34.8	9.4	14.8	11	6.1	5	10.4	84.2
33.5	17.7	28.3	52.8	8.6	14.2	10.8	7.1	7.7	16.3	78
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
41.39	23.38	17.34	50.03	10.93	17.25	13.1	8.4	6.09	10.92	80.61
38	32.8	96.2	88.7	4.4	10.5	9.9	13.7	30.6	15.4	77.3
42.7	45.2	36.8	33.7	11.7	29.1	15.1	16.2	14.6	7.6	80.5
32.8	15.2	9	25.5	8.5	15.1	7.5	4.3	2.6	3.3	85.9
25.3	12.3	8	28	7.1	12.2	7.1	3.7	2.5	4.5	85.6
38.2	23.2	10.7	80.8	18.6	17.4	11.1	7.7	3.6	13.3	78.2
71.3	14.8	11.3	20.7	7.5	26.6	25.1	7.4	5.9	5.7	86.4
35	21.5	14.5	31.3	6.7	9.7	9.4	7.3	5.1	8.4	81.7
57.3	29.7	15.7	90.2	10	19.2	17.5	9.8	5.6	19.3	80.5
39.3	29.5	25.8	63.8	8.9	13.7	13.2	10.3	8.6	15.6	79.6

12ctMH2	12ctMH3	12ctMH4	12ctMH5	12ctHx	12mfMH1	12mfMH2	12mfMH3	12mfMH4	12mfMH5	12mfHx
83.3	79.2	75	75	62.5	20.9	40.7	26.9	12.9	4.6	20.3
87.5	87.5	83.3	79.2	75	20.5	41.4	31.8	14.2	6.1	14.3
83.3	83.8	83.83	83.3	82.7	22.2	28.6	23.8	10.6	5.6	24.5
79.2	81.9	85.4	85.4	67.2	24.1	22.4	21	12.6	7.1	22.6
87	86.1	88.7	86.1	81.7	23.2	46.3	25.8	12.5	5.6	14.9
86.9	86.9	87.8	87.8	80.4	32.2	35.8	23.1	9.1	5.6	25.8
95.8	95.8	91.7	82.1	70.2	24.7	37.6	27.6	11.5	5	11.6
82.7	82.7	86.9	82.7	34.5	26.5	23.1	24.9	20	11.4	3.9
83.8	87.4	86.5	85.6	78.4	13.6	24	29.4	12.7	6.5	8.4
82.1	86.9	82.1	82.1	54.8	21.4	27	33.2	16.5	7.5	20.3
77.8	77.8	77.8	77.8	58.3	29.7	28.7	28.3	13.4	6.7	22.2
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
87.72	89.7	89.78	85.02	67.11	12.5	20.32	32.57	21.6	6.07	14.53
83.32	85.18	84.23	80.67	39.91	29.41	26.85	28.72	12.2	3.86	9.42
71.3	73.4	73.4	73.4	65.9	9.5	28.2	24.8	14.6	5.4	9.9
85.2	87.8	88.7	81	78.3	13.3	30.3	21.4	14.3	6.7	21.1
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
80.9	81.6	77	70.4	70	31.6	27.2	19.2	9.2	3.2	18.1
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
83.2	84.2	79.2	73.3	72.3	30.4	23.3	19.6	10.9	3.7	12.2
85.8	83.9	81	77.2	62.8	31.7	26.4	22	10.8	4	8.1
89	89.9	88.9	86	82.2	31.2	19.2	20.3	11	4.1	22.6
85.7	85.7	85.7	84	68.9	17.2	25.9	24.2	13.9	5.5	8.5
82.1	83.7	82	83.7	60.9	22.7	24.9	18.9	12	5.3	17.3
81	82.7	81.9	83.7	68.9	29.4	25.9	24.1	12.1	4.8	8.6
86.5	89.4	88.5	88.5	86.6	19.6	26	22.9	13.4	6.3	14.9
89.8	91.8	91.6	89.8	89	13	17.9	20.2	12.9	7.6	24.6
86	87.9	89.8	88.9	84.2	21.6	25.1	18.3	9.5	6.2	17.8
82.2	86.4	86.5	83	83.1	19.8	25.5	19.4	12.4	9.5	22.7
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
84.34	85.5	84.72	81.93	69.07	22.55	27.41	23.86	13.05	6.79	16.56
77.3	81.1	85.9	82.1	57.6	12.5	23	20.9	17	22.5	28.3
87	90.3	89.5	82.2	61.7	19	25.5	19.5	18.7	11.4	12.1
88	88	85	79.6	41.2	32.9	31.1	21.6	12.5	4.9	15.9
87.8	86.7	82.2	76.7	55.6	28.8	33.3	18	11.2	6	18.2
83.8	85.7	83.9	79.1	67.7	28.6	23.8	20	10.2	3.3	20.4
88.6	89.3	89.3	86.4	67.7	14.9	24	28.6	12.6	6.5	13.9
82.7	84.6	85.6	79.8	88.4	18.4	20.5	23.2	17.2	8.7	13.7
85.6	84	83.1	85.6	73.1	22.4	27.3	27.7	13.4	5.7	17.4
82	83.7	83.6	80.4	78.8	19.8	22.3	23.4	7	14.8	20.6

12ftiMH1	12ftiMH2	12ftiMH3	12ftiMH4	12ftiMH5	12ftiHx	18ppH	18ppMH1	18ppMH2	18ppMH3	18ppMH4
6.5	14.5	10	4.9	1.7	3.6	28.5	58.3	91.8	49.3	23.2
7.7	15.6	12.8	6.2	2.4	2.9	23.8	41.8	88.3	53.8	19.8
8.1	10.8	9.7	4.5	2.3	5.9	33	40.65	59.79	42.39	22.33
7.5	8	7.9	4.5	2.3	5.4	28.8	35.5	20.5	18.7	8.5
6.6	15	9.8	5.3	2.5	3.5	33	40.65	59.79	42.39	22.33
8.4	11.2	8.1	3.7	2.2	5.7	33	40.65	59.79	42.39	22.33
9.3	14.2	9.9	4.1	1.5	2.4	50.8	38	109.2	44.7	17
9.5	7.4	8.8	8	4.4	0.5	33	40.65	59.79	42.39	22.33
4.7	8.9	10.2	5.1	2.3	2.8	31	23.8	84.7	75.2	30.5
5.2	7.7	9.8	5.2	2.5	3.6	31.3	29.3	37.7	34.5	22.8
6.3	8.9	9.6	5.5	2.7	3.5	27	36.5	45.2	38.7	19.8
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
3.08	5.31	9.75	15.78	10.83	3.07	34.8	13	32	53	47.2
6.77	8.03	9.53	4.41	1.34	1.38	33	40.65	59.79	42.39	22.33
3.8	9.8	10.2	6	1.7	2.4	33	40.65	59.79	42.39	22.33
4.5	12.2	9.8	5.3	1.5	6.1	25.8	23.7	85	54.7	38
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
10.7	10.2	7.5	3.6	1.1	3	55.8	42.2	44.2	40.7	21.3
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
9.1	8.1	7.1	3.6	0.9	2.7	30	29.5	33.3	23.7	17.7
8.8	8.4	6.9	3.4	1.1	1.4	31.2	41	25.8	25	13.5
10.5	6.2	6.8	3.8	1.3	4.7	33	40.65	59.79	42.39	22.33
5.2	9.2	9.4	5.1	1.8	1.9	55.7	102.5	76.7	33.2	21.2
7.6	9.4	8.3	4.5	1.9	3.5	41.7	98.2	46.2	31.5	15.5
10.6	8.6	7.3	3.6	1.3	1.6	28.5	67.2	37	36.7	18.8
6.1	9.3	7.7	5.1	2	3.3	32.8	41.2	91.7	78	23.2
4.2	6.8	7.9	5	2.8	6	29.7	26.5	48	42.2	17.8
8.6	9.7	7.5	4	2.2	5.3	21.8	26.8	44.3	36.3	16.7
7.5	9.7	8.3	5	2.7	7.1	22	33.5	48.2	41.7	18.2
7.1	9.52	8.7	5.25	2.51	3.56	26.5	50.2	68	59.7	26.3
7.1	9.52	8.7	5.25	2.51	3.56	26.2	42.7	59.7	42	26.2
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
7.1	9.52	8.7	5.25	2.51	3.56	33	40.65	59.79	42.39	22.33
2.5	5.7	6.3	6.3	7.5	4.5	33	40.65	59.79	42.39	22.33
6.9	9.6	8.2	8	4.7	2.8	36.8	53.2	82.5	34.7	44.3
8.5	8.5	6	3.6	1.4	2	33	27.3	66.7	35.8	18.8
7.8	9.3	5.7	3.3	1.5	2.9	27.7	26	68.7	30	12.5
7.9	7.7	6.9	3.5	1	3.7	63.8	66.7	94	39.8	22.7
6.5	12.2	13.8	7.1	3.2	3.6	25.3	25.3	58.8	49.3	13
6.6	7.2	8.1	6.3	2.9	3.5	22.7	31.7	32.8	32.2	19.8
7.8	10.8	10	4.9	1.9	3.7	31.8	29	76	56.3	21.5
7.2	8.9	9.1	5.7	2.5	4.7	32.5	18.2	36.8	37.8	31.8

18ppMH5	18ppHx	18ptiMH1	18ptiMH2	18ptiMH3	18ptiMH4	18ptiMH5	18ptiHx	18ctMH1	18ctMH2	18ctMH3
10.7	48.5	16.7	27.9	15.7	7.9	4.2	9.3	77.5	83.9	84.7
11.5	90.5	14.4	27.4	18.4	8.4	4.7	20.6	80.3	85.9	86.6
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
6.2	66.8	10.6	7	6.5	3.2	2.1	18.8	75.2	75.2	79
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
16.7	103	14.2	33.1	16.3	6.1	4.7	14.6	86.8	89.3	90.9
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
21.3	41.8	7.8	23.5	20.6	9.5	7.1	12.4	79.5	86.3	87.2
14.8	37.2	7	10.5	9.7	6.8	4.7	6	79.7	81.5	87.1
17	39.3	8.3	12.3	11.5	6.7	5.7	7.6	77	83.2	85.8
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
20.7	24.7	4.7	12	17.2	15.5	7.1	5.7	79.5	87.4	88.2
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
24.3	119.3	9.3	23.5	20.5	15.2	8.4	35.4	81.9	87.4	89.2
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
8.7	40.8	14.7	14.3	12.5	7.4	3	6.6	84.3	87.6	87.6
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
8.3	32.5	9.4	9.8	8.7	6.6	2.4	8.1	86.1	85.2	85.2
6.7	27.2	10.8	8.5	8.2	4.6	2.5	5.6	84.1	85	85.9
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
7	43.2	22.6	21.7	11.9	8	2.8	7.7	81.4	84.7	83.1
5.2	59.5	36.4	16	11.5	6.6	2.4	14.4	82.4	82.5	83.3
9.7	32.2	21	11.4	10.4	5.1	2.8	7.4	76.7	79.3	80.2
10	21.7	13.4	25.7	20.7	7.4	3.6	5.4	89	89	89
13.2	99.2	8.4	13.9	12.3	6.8	5	22	89.4	91.4	92.3
11	31	9.2	12.9	10.9	6.6	5.1	9.1	81.3	83.2	86.9
14.3	56	11.1	12	10.5	6.5	3.9	19.2	83	84.9	88.7
13.7	22.8	16.3	18.9	16.6	8.2	4.9	4.7	87.1	88.9	89.9
29.5	20.2	15.4	17.4	13.5	9.1	8.4	5.8	86.2	87.8	87.8
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
14.65	50.47	12.8	17.06	13.03	7.74	4.89	11.71	82.02	85.26	86.48
32.2	39.8	15.2	26.3	13.03	15.7	12.8	11.4	77.8	86.3	91.5
12.3	17.2	6.9	13.6	7.7	4.8	3.4	2.1	85.4	87.7	87.7
8.7	24.2	8.3	14.9	8.8	4.2	2.9	4.3	87	89.1	87
10.5	73	18.5	17.9	11.3	8	3.9	11.6	77.7	84.2	85.2
6.3	42.3	10.6	19	15.7	5.6	2.7	13.4	82.5	87.9	87.1
13.2	38.2	10.9	8.9	8.6	6.6	4.9	12.4	82.7	83.6	86.4
11.5	106.2	11.5	22.4	17.6	7.8	4.7	22.5	75.1	79.4	77.3
49.7	65.3	7.5	12.1	12	9.7	11	15.6	81.9	84.6	87

18ctMH4	18ctMH5	18ctHx	18mfMH1	18mfMH2	18mfMH3	18mfMH4	18mfMH5	18mfHx	18ftiMH1	18ftiMH2
84.7	82.3	62.8	18.5	40.1	26.1	13.5	5	17.6	6	14.7
85.1	79.5	72.4	19	38.6	29.7	12.5	5.4	18.1	7.4	15.3
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
80.9	67.6	76.2	32.6	19.8	14.6	7.8	4.5	33.2	10.6	7.1
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
86	78.5	75.3	25.3	42.1	26	11.9	5.1	13.2	9	15.8
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
86.3	85.5	76.2	16.4	25.7	30.1	13.7	6.1	8	5.5	10.2
85.3	84.3	58.6	18	26.3	30.8	15.9	8.1	22.7	5	8.1
84.1	84.9	62.7	28.3	27.7	28	12.9	7.8	24.7	6.4	8.7
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
88.2	84.2	66.1	13	20.9	34.9	24	6	12.8	3.9	7.6
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
88.3	82.8	82.8	13.9	27.2	19.4	12.3	6.9	19.3	4.6	10.3
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.3	82.6	65.3	35.2	25.9	19.4	10.4	2.8	23.7	11.8	9.4
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
79.6	63.9	78.7	30	22.9	20.7	12	4.8	13.3	9.9	9.2
84	81.2	83.1	34.5	26.2	21.5	9.9	3.7	10.7	10.5	9.2
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
79.7	79.7	66.9	31.8	26.6	22.5	11.4	3.6	10.7	8.4	9.3
81	80.2	75.4	33.5	21.2	16.1	8.2	2.5	21.8	13.2	9.1
78.5	80.2	69.8	28.3	22.1	18.6	7	2.6	12.6	9.4	7.4
88.1	85.3	73.4	23.3	25.2	21.6	9	3.8	13.6	8.1	9.7
90.4	87.5	76.2	18.5	19.8	19	10.5	5.3	20.1	5.5	6.8
87.9	88.8	79.5	24.9	25.8	19.9	10.8	6.7	18.9	9.1	9.6
87.8	82.1	81.9	27.2	28.6	25.8	11.6	7.3	25.5	9.2	8.6
88	81.5	79.5	29.8	27.7	24.4	10	5.3	9.3	9.9	9.6
85.4	82.1	74.9	24.2	25.9	23.8	17.9	10.4	8.4	9.3	10
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
84.93	81.02	72.63	25.13	26.8	22.56	12.53	7.99	17	8.24	9.63
88.9	83.8	71.1	22.4	22.4	16.8	18.7	9.1	14.8	7.2	8.2
87.7	80.9	39.3	28.3	34	23.3	16.3	72	11.1	6.5	8.2
84.8	80.4	63	29.1	34.8	19.3	11.9	6.3	16	8.8	10.4
84.3	80.5	61.6	25.6	24.7	19.7	11.4	4.3	18.9	7.3	8.2
85.5	77.9	79.3	29	26	21.6	8.6	3.5	21.1	11.8	11.9
86.4	83.6	90	25.3	20.4	22	15	7.1	16.9	9.3	7.1
75.8	75.8	77.2	26.3	28.8	23.6	10.4	4.3	18	9.3	11.9
86.1	82	87.1	16.7	19.9	15.2	17.8	11.4	18	6.2	7.8

18ftiMH3	18ftiMH4	18ftiMH5	18ftiHx	24ROM	df	pf	24ppMH1	24ppMH2	24ppMH3	24ppMH4
9.9	5.3	1.8	3.1	96	90	6	67	102.3	55.8	19.7
12	5.5	2.1	3.9	86	80	6	40.5	89.3	51.8	21.8
8.34	4.67	1.9	4	80	75	5	43.5	65.3	54.2	18.2
5.1	2.3	1.2	9.2	70	65	5	26.7	21.8	20.8	10.3
8.34	4.67	1.9	4	84	72	12	68.7	113.5	41.7	22.5
8.34	4.67	1.9	4	86	74	12	97.8	83.2	34	16.3
9.7	4.2	1.5	2.4	100	85	15	17.3	94.3	50.8	22.8
8.34	4.67	1.9	4	75	70	5	101.7	44.5	43.8	34.5
11	5.6	2.3	2.5	100	90	10	23.5	82.8	76.3	29.5
9.2	5	2.6	3.9	100	90	10	29.8	36	33	21.3
9.1	5	2.7	4.5	100	90	10	48.7	37.2	33.2	16.5
8.34	4.67	1.9	4	70	65	5	69.5	76	45	35.3
8.34	4.67	1.9	4	70	65	5	115.5	48.3	40	22.5
13.3	9.2	2.5	3	45	45	0	10.7	29.3	65.3	47.2
8.34	4.67	1.9	4	60	70	-10	24.7	48.7	45.2	31.2
8.34	4.67	1.9	4	80	70	10	20.7	57.8	46.5	42
8.5	5.4	2.1	5.7	88	70	18	32.7	87.2	56.7	42.5
8.34	4.67	1.9	4	70	60	10	23.3	61.3	28.7	23.8
7	3.8	1	3.9	90	80	10	43.2	42.3	45	20.5
8.34	4.67	1.9	4	90	70	20	22.5	80	97.3	81.5
8.34	4.67	1.9	4	82	73	9	46.8	60.3	43.9	24.8
8.2	4.2	1.2	3.3	95	85	10	33.2	34.2	25.5	18.8
7.5	3.4	1.2	2.3	100	80	20	44.8	25	24.5	11.3
8.34	4.67	1.9	4	75	65	10	52.5	33	30.7	24.3
8.5	4.3	1.2	2.3	100	90	10	79.3	78.8	54.2	25.5
7.4	3.5	0.8	5.3	100	90	10	76	48	32.7	13.7
5.9	2.3	0.9	2.9	70	60	10	57.7	34.5	34.8	18.2
7.6	3.5	1.4	3.2	100	90	5	57.7	100.8	87	23.8
6.9	3.8	1.8	4.4	100	90	10	28	50.2	45.5	18
8	4.4	2.2	5.5	80	70	10	22.5	46.2	32.5	20.2
8.3	4.2	1.7	8.1	90	80	10	30.8	42.3	36.2	21.3
8.2	4.1	1.9	2.1	60	50	10	58.8	66.8	58	27
8.8	6.7	3.4	2.4	60	50	10	96	65	42.2	21.2
8.34	4.67	1.9	4	70	65	5	30.5	59.7	38.2	21.5
8.34	4.67	1.9	4	80	70	10	27.2	55.5	50	23.8
8.34	4.67	1.9	4	75	65	10	19.8	42.7	38	34
6.7	7.7	4	3.7	110	90	20	65.5	94.7	33.5	36.5
6.1	4.5	1.9	1.3	80	70	10	34.3	83.3	32.2	17.2
6.9	3.8	1.7	2.7	80	70	10	26.7	61.3	27.5	13
7	4.1	1.4	3.3	75	65	10	124.3	74	32.7	19.7
9.7	3.9	1.3	6.7	90	80	10	24.5	48.3	42	10.7
7.6	5.8	2.7	4.9	80	75	5	44.7	33.2	30.5	15
9.2	4.3	1.7	4	70	60	10	30.7	75	57.7	23.5
8.7	5.6	2.8	4.1	70	60	10	20.5	39.3	38.5	29

24ppMH5	24ppHx	24ptiMH1	24ptiMH2	24ptiMH3	24ptiMH4	24ptiMH5	24ptiHx	24ctMH1	24ctMH2	24ctMH3
9.3	69.2	19.3	30.7	17.1	7.6	4.4	14	79.3	84.9	86.5
12.5	83.3	14.2	28.7	18.6	9.2	5.7	15.9	80.9	85.5	86.3
11.2	99.7	14.2	23.9	18.4	7.6	5.2	19.9	86.5	87.3	89
6	50.2	9.4	7.8	7.5	4.2	2.3	14.1	76.8	77.8	80.6
11.5	51.8	16.3	33.7	13.5	8	4.8	11.5	80.5	88.9	86.5
21.7	99	26.2	24.6	12.3	6.2	7	20.7	81.9	87.1	87.1
22.5	92.2	5.4	23.7	14.6	6.3	4.6	21	80.2	85.4	87.2
32.5	8.5	32.7	12.1	13.1	11.8	11	0.9	83.7	88	88.9
22.2	42.5	7.6	24.5	21.1	9	7	14.3	82.3	85.8	87.6
12.8	35.8	6.8	10.6	9.9	6.8	4.4	5.3	83.1	85.8	87.5
9.5	40.2	11.1	11	10.4	5.6	3.9	7.1	81.1	85.4	87.1
101	62	20.1	22.2	16	13.2	31.1	18.7	81.7	81.7	84.9
24.3	43.5	35.9	14.9	13.4	8.4	7.6	10.8	91.7	88.9	89.8
18.8	27	4.6	13.4	22.5	18.3	7.5	6.7	78.1	87.1	90.2
12.5	16.8	6.5	13.4	13	10.3	4.9	2.6	79.8	84.4	86.2
10.7	30.2	5.2	14.9	14.3	13.8	4.4	5.9	70.3	82	85.6
33	113	12.5	27.6	23	19.5	8.3	32.4	80	85.2	87.8
16.8	19	7.4	15.2	8.1	6.3	4.8	5.5	80	85.2	85.2
6	27	16.4	15.3	13.4	6.5	1.8	4.9	86.6	71.3	71.3
40.8	18.5	11.5	32.1	39	29.6	18.9	5.8	89	90.4	90.4
18.7	51.6	14.8	18.1	14.1	8.8	6.2	12.5	82.3	84.9	86.1
11	36	9.3	9.7	8.8	7.3	3.2	8.5	78.5	78.5	78.5
6.2	30.7	12.5	8.6	8.4	4.2	2.5	6	84.3	84.3	86.3
11.8	68.7	15.7	9.4	9.3	7.5	3.3	15.2	86.1	87	89.8
9.7	46.7	23.1	23.8	17	9.1	3.3	9.7	81.5	84	84
12.5	67.3	27.5	16	12.1	6.1	3.8	15.1	80.9	85.2	84.4
10.5	30.7	20	11	10.2	5.1	3.1	6.9	79.1	79.9	79.9
10.2	24.5	18.5	31	24.3	7.2	3.5	7.4	87.4	91	90.1
12.2	99.5	10.7	16.8	14.6	7.2	4.8	31.3	88.5	90.2	91.8
11.8	35	8.3	14	10.1	6.6	4.4	7.6	86	88	89
22.8	45.5	7.9	10.4	8.8	6.8	6.4	12.2	84.8	86.8	90.9
18.3	23.3	14.8	18.8	16.1	8.8	7	4.9	82.2	83	85.5
18	23	27.4	16.6	12.5	7.2	5.8	6.9	84.3	84.3	86
4	37.3	11.6	25.7	19	9.9	2.1	12.8	83.4	87.8	88.5
6.2	58.2	12.4	19.9	19.7	10.1	2.5	28.2	80.6	83.8	83.8
78.5	100.2	6.4	11.6	10.1	12.8	22.7	23.1	78.6	80.6	82.5
32.7	46	20.8	29.8	11.3	12.7	10.6	11.7	78.1	86	86.2
10.7	22.7	8.9	16.3	7.3	4.5	3	2.8	86.3	87.4	88.4
8.8	20.7	8.4	14	8.4	4.3	3	3.5	86.1	86.1	86.1
7.8	99.8	39.5	14.5	9	6.3	2.6	19.1	82.1	85.8	84.9
4.7	52.7	12	19.7	15	5.1	2.3	15.1	82.8	85.8	85.8
10.3	33.2	15.2	8.8	7.9	5.3	3.6	10.5	83.1	83.1	85
8.3	107.2	12	20	15.9	7.7	3.5	24.1	81.9	83.6	84.5
42.8	79.5	8.4	13.4	13	10.1	11.3	15.7	80.5	81.9	85

24ctMH4	24ctMH5	24ctHx	24mfMH1	24mfMH2	24mfMH3	24mfMH4	24mfMH5	24mfHx	24ftiMH1	24ftiMH2
86.4	84	68.1	21.1	38	26.5	12.3	4.8	23.2	7.3	14.7
84.7	82.4	71	21.7	40.7	31	13.9	6.1	16.6	8.4	16.1
89	89	88.1	24	30.2	23	9.8	4.9	24.3	8.9	12
84.3	75.8	70.3	31	21.6	17	8.4	4.6	29.5	10.6	7.9
86.5	86.5	82.2	19.6	43.4	21.4	11.2	4.6	12.2	5.8	15.1
85.4	83.7	79.4	22.5	32.7	21.5	9.4	6.2	18	6.9	11.4
84.5	74.7	84.1	15.1	35.2	30	17.3	7.7	13.5	4.6	11
89.9	86.3	23.1	25.6	18.7	21.4	19.7	12.4	2.4	8.7	5.4
87.6	85.8	76.1	14.8	23.3	29	12.8	6.1	9.6	4.7	9.5
85.7	85.8	51.7	21.4	26.4	30.9	15.9	7.3	20.5	5.3	8.2
81.9	86.3	69.9	33.2	26.1	24.8	10.2	4.2	25.8	8.4	8.7
86.5	84.1	82.5	17.4	21	17.3	12	14.4	13.2	6	8
90.7	88.9	87	27.6	21.3	18.7	12	7.1	11.1	9.9	7.2
89.5	84.2	78.9	10.6	17.5	33.2	22.6	5.9	11.7	3.7	8
86.2	86.2	39.6	27.9	32.3	29.4	15.6	5.1	10.3	6.2	9.8
86.5	84.7	56.8	17.7	31.5	29.3	15.2	4.7	18.9	3.7	9.2
86.9	80.1	79.2	11.6	29.8	20.1	16.3	9.5	19.5	4.4	11.7
86.1	87.8	72.2	29.1	36	23.6	16.1	8.3	17.4	8.2	10.9
68.8	60.5	63	32.7	26.9	23.6	10	2.1	13.3	12.5	10.2
91.2	89.8	78	12	24.9	24.3	18.8	9.6	6.1	5.8	12
85.3	82.2	73.1	24.7	27.1	23	12.5	6.1	16.8	8.2	9.8
76.6	73	69.7	27.9	23.4	21.1	12.8	5.5	12.3	9.1	8.9
83.3	81.4	75.6	34.5	24.9	19.3	8.2	3.8	12.1	10.8	9
87	83.3	79.9	26.3	23.6	22.9	12.8	5.4	19.7	8.3	7.5
82.3	81.4	73	26.7	24.9	25.5	12	3	12.2	8.9	9.5
82.6	83.5	75.6	27.8	20.4	15.6	9	3	22.2	11.2	8.9
79.9	81.7	73	36.8	27.9	22.7	8.7	3.6	15.9	13.1	9.6
87.4	85.6	77.5	25.7	26.1	20.5	8	3.2	14.7	9.4	10.5
91.8	88.5	87.6	19.7	21.1	19.1	10.4	5.4	22.1	7.3	8.6
92	90	76.2	19.3	27.3	21.8	11.5	7.1	21	7.5	9.7
90.9	86.8	88.9	24.3	26.9	23.8	14.1	9	23.9	6.6	7.9
85.5	77.8	72.8	27.9	27.5	25	12.3	7.3	9.6	7.5	9.2
85.2	82.7	72.8	32.9	26.6	21.7	13.2	6.5	10.3	11	9.3
87	83.5	71.1	24.6	31.3	25.8	9.3	2	12.6	9.6	15.1
83.8	77.4	88.2	20.4	27.3	28.5	10.3	2.1	14.6	9.2	12.7
85.5	82.5	82.5	15.9	23.1	20	12.8	17.7	31.4	4.9	6.7
84.7	79.1	73.1	24.9	23.2	15.9	13.7	7	15.3	8.3	7.8
83.2	78.9	44.2	36.1	36.4	21.7	14.8	6.5	14.5	8.7	9.6
81.2	74.2	52.5	31.8	32.1	21.1	12.3	6	13.5	9.6	10.2
82	80.1	77.2	38	21.8	17.2	8.6	2.6	23.2	11.6	6.7
85.1	77.7	82.8	27.2	24.5	19.6	6.7	2.4	27.5	12.4	12.4
86	75.7	91.5	31.1	20.9	17.3	12.1	6.1	13.4	11.9	7.1
81.9	81.1	79.3	28.1	26.7	21.8	8.1	3.1	19.9	10	10.5
83.4	80.4	75.8	17.4	22	24.3	16.3	9.8	23.1	6.6	8.7

24ftiMH3	24ftiMH4	24ftiMH5	24ftiHx
10.6	5.4	1.9	4.5
12.6	6.3	2.5	3.3
9.9	4.6	2.2	6.1
6.4	2.7	1.3	7.8
8.5	4.7	2	3
8.3	4.2	2.8	4.3
9.3	4.9	1.7	3.6
7	7	4.1	0.3
10.6	5.4	2.3	3
9.8	5.2	2.5	3.5
8.3	3.9	1.8	4.6
7.2	5.4	5.5	3.8
6.9	4.9	2.7	2.6
14.5	9.7	2.6	3.5
10.2	5.8	1.9	1.5
10.4	6.1	1.7	3.2
9.4	5.9	2.2	5.9
7.3	5	2.4	3.9
8	3.2	0.6	2.4
12.7	10.4	5	1.9
8.6	4.8	2.1	4
8.4	4.3	1.4	3.1
7	2.9	1.1	2.7
7.6	4.2	1.6	3.9
10	4.6	1	3
7.2	3.2	1	5.1
7.5	3.1	1.3	3.6
7.3	3.3	1.1	4.2
7.7	4.1	2	6.5
8	4.4	2.3	4.5
7.8	5.5	2.7	6
8.7	5.3	2.9	2.1
7.6	5.3	2.6	3.1
12.6	4.2	0.8	3.6
12.8	4.4	0.8	6.3
6	4.7	5.5	6.3
6.1	5.2	2.8	3.7
5.9	4.3	1.8	1.7
7.3	4.1	1.7	2.2
5.5	2.8	0.7	4.7
9.6	3.6	1	8.6
6.3	4.4	1.8	4.1
8	3.4	1.2	4.7
9.2	6	3	4.4

pp = peak pressure, pti = pressure-time-integral, ct = contact time, mf = maximum force, fti = force-time-integral
MH1 = 1st metatarsal head, MH2 = 2nd metatarsal head, etc, Hx = hallux.

APPENDIX L

RELIABILITY OF RADIOGRAPHIC MEASUREMENT RAW DATA

Dorso-Plantar View

X-ray	MA	MPA	HA	HIPA	MPD mm	4IMA	MW mm	MBA
1.1	20	14	17	9	0	10	90	141
1.2	20	13	16	8	0	8	89	140
1.3	20	13	18	9	0	8	89	141
2.1	20	10	16	22	0	8	90	140
2.2	19	11	17	18	0	9	90	142
2.3	18	12	18	18	0	10	90	140
3.1	15	10	16	9	0	8	72	148
3.2	13	8	13	7	0	7	72	149
3.3	16	8	14	6	0	8	72	148
4.1	27	11	27	2	2	7	88	148
4.2	29	10	27	2	2	5	89	145
4.3	25	12	26	6	2	5	89	145
5.1	24	5	20	5	1	8	84	145
5.2	25	6	22	6	1	8	87	146
5.3	22	5	23	6	0	8	84	147
6.1	25	13	28	5	0	7	97	139
6.2	25	15	30	10	0	8	98	138
6.3	24	14	31	6	0	9	98	138

MA=metatarsus adductus angle
MPA=metatarsus primus adductus angle
HIPA=hallux interphalangeal angle
MPD=1st metatarsal protrusion distance
4IMA=4th intermetatarsal angle
MW=metatarsal width
MBA=metatarsal break angle

Lateral View

X-ray	CIA	TDA	TCA	1MDA	5MDA	1/2IMA	NHt mm
1.1	27	20	51	22	12	0	40
1.2	26	22	50	22	16	0	40
1.3	27	23	53	24	16	0	40
2.1	25	26	48	21	9	4	39
2.2	24	22	46	19	12	3	40
2.3	24	24	48	20	11	2	38
3.1	22	17	40	24	12	2	42
3.2	23	20	44	23	12	0	41
3.3	22	20	42	26	13	0	42
4.1	28	17	45	23	14	10	40
4.2	27	22	48	23	12	4	45
4.3	27	20	46	22	11	4	46
5.1	27	22	47	31	13	5	50
5.2	30	20	48	28	12	2	51
5.3	30	20	50	28	13	2	51
6.1	23	33	55	18	7	0	37
6.2	23	30	53	20	6	0	37
6.3	21	33	53	17	4	0	37

CIA=calcaneal inclination angle
TDA=talar declination angle
TCA=talo-calcaneal angle
1MDA=1st metatarsal declination angle
5MDA=5th metatarsal declination angle
1/2IMA=1st/2nd intermetatarsal angle
NHt=navicular height

APPENDIX M

PRE-AND POST-OP HALLUX VALGUS X-RAY MEASUREMENTS

Subject	pre mpa	post mpa	pre-post mpa	pre ha	post ha	pre-post ha	pre mpd	post mpd	pre-post
1	10	6	4	22	10	12	8	1	
2	9	4	5	26	16	10	8	1	
3	14	10	4	26	10	16	8	1	
4	10	4	6	25	10	16	1	-3	
5	12	7	5	18	0	18	0	-6	
6	14	8	6	20	10	10	2	-4	
7	13	7	8	31	15	16	0	-4	
8	15	8	7	28	16	12	-1	-8	
9	15	6	7	31	6	25	9	-2	1
10	16	7	9	26	4	22	4	-2	
11	16	7	9	26	8	18	3	-3	
12	18	6	12	37	4	33	10	0	1
13	18	8	10	38	8	30	10	1	
14	12	7	5	24	0	24	2	-6	
15	11	6	8	22	12	19	5	-1	1
16	9	4	5	26	10	16	5	-3	
17	12	8	4	26	12	14	2	-5	
18	12	6	6	24	10	14	2	-4	
19	10	7	9	20	-4	24	0	-2	
20	12	0	12	24	20	4	2	2	
21	6	3	3	23	7	15	0	-4	
22	16	5	11	30	9	21	4	-1	
23	18	8	10	38	16	22	4	0	
24	12	6	6	35	8	27	2	-2	
25	13	5	8	35	10	25	5	-3	
26	11	5	6	22	10	12	2	-5	
27	15	3	12	24	0	24	0	-5	
28	10	7	3	25	7	18	0	-2	
29	14	5	9	30	12	18	0	-5	
30	18	8	10	30	4	26	-1	-1	
31	12	8	4	24	10	14	2	0	
32	17	6	11	36	14	22	0	-5	
33	12	6	6	24	16	8	2	-5	
34	14	6	8	25	12	13	6	1	
35	15	4	11	30	10	20	5	-1	
36	9	6	3	20	10	10	-1	-1	
37	16	10	6	23	8	15	0	0	
38	10	3	7	30	12	18	-2	-6	
39	11	7	4	24	16	8	-2	-5	
40	10	7	3	20	4	16	2	-5	
41	11	6	5	32	10	22	2	-4	
42	15	5	10	28	10	18	0	-5	
43	16	8	8	35	19	16	0	-5	
44	15	6	9	30	8	22	0	-4	

mpa = metatarsus primus varus (°), ha = hallux abductus (°), mpd = 1st metatarsal protrusion distance (mm)

APPENDIX N

CORRELATION OF PRE-AND POST-OPERATIVE PLANTAR PRESSURE MEASUREMENTS WITH X-RAY MEASUREMENTS IN HALLUX VALGUS GROUP

N=44			Pre-operation			24 months post-operation		
			MPA	HA	MPD	MPA	HA	MPD
Peak pressure	MH1	Pearson Corr.	0.360*	0.104	0.231	0.235	-0.087	-0.135
		Sig.(2-tailed)	0.016	0.502	0.132	0.064	0.145	0.049
	MH2	Pearson Corr.	0.007	0.080	0.017	0.064	0.145	0.049
		Sig.(2-tailed)	0.963	0.606	0.915	0.678	0.348	0.751
	MH3	Pearson Corr.	0.148	0.138	0.183	-0.190	0.144	0.168
		Sig.(2-tailed)	0.338	0.372	0.233	0.216	0.351	0.275
	MH4	Pearson Corr.	-0.197	-0.167	0.294	-0.272	0.135	0.178
		Sig.(2-tailed)	0.201	0.277	0.053	0.074	0.384	0.247
	MH5	Pearson Corr.	0.096	0.106	0.172	0.013	-0.012	0.166
		Sig.(2-tailed)	0.535	0.491	0.265	0.932	0.940	0.281
	HX	Pearson Corr.	-0.274	-0.509**	0.054	0.233	0.079	0.024
		Sig.(2-tailed)	0.071	<0.001	0.726	0.128	0.608	0.879
Pressure-time-integral	MH1	Pearson Corr.	0.279	0.124	0.230	0.177	-0.066	-0.122
		Sig.(2-tailed)	0.067	0.422	0.133	0.249	0.671	0.431
	MH2	Pearson Corr.	0.002	0.061	0.101	0.015	0.114	0.242
		Sig.(2-tailed)	0.989	0.695	0.515	0.921	0.461	0.113
	MH3	Pearson Corr.	0.043	0.074	0.209	-0.260	0.191	0.280
		Sig.(2-tailed)	0.781	0.635	0.173	0.088	0.215	0.065
	MH4	Pearson Corr.	0.087	-0.074	0.111	0.085	-0.246	0.156
		Sig.(2-tailed)	0.574	0.631	0.473	0.107	0.311	0.162
	MH5	Pearson Corr.	0.117	0.095	0.146	-0.064	0.040	0.234
		Sig.(2-tailed)	0.451	0.542	0.343	0.682	0.798	0.127
	HX	Pearson Corr.	-0.280	-0.519**	0.112	0.120	0.092	0.047
		Sig.(2-tailed)	0.066	<0.001	0.468	0.444	0.552	0.760

Contact time	MH1	Pearson Corr.	0.142	0.308*	0.022	0.110	0.121	0.166
		Sig.(2-tailed)	0.359	0.042	0.885	0.479	0.433	0.281
	MH2	Pearson Corr.	-0.005	0.172	0.066	0.139	0.289	0.013
		Sig.(2-tailed)	0.977	0.263	0.670	0.367	0.057	0.932
	MH3	Pearson Corr.	-0.026	0.068	0.033	0.162	0.333*	0.058
		Sig.(2-tailed)	0.865	0.660	0.830	0.295	0.027	0.707
	MH4	Pearson Corr.	0.003	-0.083	0.135	0.082	0.247	0.143
		Sig.(2-tailed)	0.595	0.107	0.355	0.982	0.593	0.381
	MH5	Pearson Corr.	0.062	0.034	0.223	0.058	0.124	0.190
		Sig.(2-tailed)	0.691	0.824	0.147	0.707	0.424	0.217
	HX	Pearson Corr.	0.010	0.068	0.223	0.076	-0.132	0.245
		Sig.(2-tailed)	0.949	0.660	0.146	0.624	0.393	0.109
Maximum force	MH1	Pearson Corr.	0.248	-0.017	-0.104	0.013	-0.003	-0.201
		Sig.(2-tailed)	0.104	0.915	0.502	0.931	0.986	0.191
	MH2	Pearson Corr.	-0.310*	-0.156	-0.016	-0.055	0.120	0.086
		Sig.(2-tailed)	0.041	0.313	0.919	0.721	0.438	0.578
	MH3	Pearson Corr.	0.081	0.123	0.280	-0.163	-0.017	0.135
		Sig.(2-tailed)	0.601	0.426	0.066	0.290	0.911	0.382
	MH4	Pearson Corr.	-0.186	0.013	0.067	-0.095	0.117	-0.116
		Sig.(2-tailed)	0.227	0.933	0.667	0.541	0.449	0.454
	MH5	Pearson Corr.	-0.016	0.006	-0.024	-0.011	0.049	0.147
		Sig.(2-tailed)	0.916	0.971	0.877	0.754	0.342	0.761
	HX	Pearson Corr.	-0.489**	-0.648**	-0.295	0.116	-0.148	0.073
		Sig.(2-tailed)	0.001	<0.001	0.052	0.455	0.338	0.639
Force-time-integral	MH1	Pearson Corr.	0.190	0.026	-0.064	-0.044	-0.019	-0.094
		Sig.(2-tailed)	0.218	0.867	0.680	0.778	0.904	0.545
	MH2	Pearson Corr.	-0.268	-0.092	-0.006	-0.153	0.135	0.276
		Sig.(2-tailed)	0.078	0.558	0.967	0.323	0.383	0.070
	MH3	Pearson Corr.	-0.189	-0.012	0.111	-0.247	0.061	0.291
		Sig.(2-tailed)	0.939	0.475	0.112	0.105	0.692	0.055
	MH4	Pearson Corr.	-0.098	0.020	0.074	-0.203	0.177	0.113
		Sig.(2-tailed)	0.527	0.899	0.634	0.186	0.250	0.464
	MH5	Pearson Corr.	0.044	0.033	0.031	-0.034	0.151	0.169
		Sig.(2-tailed)	0.777	0.833	0.840	0.828	0.329	0.273
	HX	Pearson Corr.	-0.456**	-0.605**	-0.192	0.079	-0.090	0.070
		Sig.(2-tailed)	0.002	<0.001	0.213	0.609	0.560	0.649

MH = metatarsal, HX = hallux,, *Correlation significant at 0.05 level, **Correlation significant at 0.01 level

APPENDIX O

CORRELATION OF PRE-AND POST-OPERATIVE PLANTAR PRESSURE MEASUREMENTS WITH *CHANGES* IN X-RAY MEASUREMENTS IN HALLUX VALGUS GROUP

N=44 X-ray measurement change 0-24months

			MPA	HA	MPD
Peak pressure	MH1	Pearson Corr.	-0.066	0.020	0.280
		Sig.(2-tailed)	0.672	0.899	0.065
	MH2	Pearson Corr.	-0.303*	-0.285	0.049
		Sig.(2-tailed)	0.045	0.061	0.753
	MH3	Pearson Corr.	-0.022	-0.097	0.086
		Sig.(2-tailed)	0.889	0.532	0.580
	MH4	Pearson Corr.	0.112	-0.170	-0.094
		Sig.(2-tailed)	0.470	0.269	0.545
	MH5	Pearson Corr.	0.102	0.071	-0.055
		Sig.(2-tailed)	0.508	0.648	0.723
	HX	Pearson Corr.	-0.294	-0.117	0.022
		Sig.(2-tailed)	0.052	0.451	0.886
Pressure-time-integral	MH1	Pearson Corr.	-0.047	-0.003	0.250
		Sig.(2-tailed)	0.760	0.984	0.102
	MH2	Pearson Corr.	-0.200	-0.265	0.022
		Sig.(2-tailed)	0.192	0.082	0.889
	MH3	Pearson Corr.	0.063	-0.169	0.060
		Sig.(2-tailed)	0.686	0.272	0.700
	MH4	Pearson Corr.	0.080	-0.201	-0.058
		Sig.(2-tailed)	0.605	0.190	0.710
	MH5	Pearson Corr.	0.145	0.013	-0.065
		Sig.(2-tailed)	0.348	0.932	0.674
	HX	Pearson Corr.	-0.158	-0.057	0.036
		Sig.(2-tailed)	0.307	0.711	0.819

Contact time	MH1	Pearson Corr.	0.175	0.091	-0.181
		Sig.(2-tailed)	0.256	0.559	0.239
	MH2	Pearson Corr.	-0.220	-0.207	-0.106
		Sig.(2-tailed)	0.151	0.179	0.496
	MH3	Pearson Corr.	-0.205	-0.132	-0.068
		Sig.(2-tailed)	0.182	0.394	0.661
	MH4	Pearson Corr.	-0.131	-0.083	-0.058
		Sig.(2-tailed)	0.397	0.593	0.707
	MH5	Pearson Corr.	-0.086	-0.062	0.076
		Sig.(2-tailed)	0.579	0.688	0.624
	HX	Pearson Corr.	0.030	0.162	-0.151
		Sig.(2-tailed)	0.848	0.292	0.327
Maximum force	MH1	Pearson Corr.	0.065	0.033	-0.002
		Sig.(2-tailed)	0.676	0.832	0.990
	MH2	Pearson Corr.	-0.241	-0.328*	0.021
		Sig.(2-tailed)	0.115	0.030	0.892
	MH3	Pearson Corr.	0.035	0.030	0.281
		Sig.(2-tailed)	0.822	0.847	0.065
	MH4	Pearson Corr.	-0.001	-0.135	0.046
		Sig.(2-tailed)	0.995	0.383	0.769
	MH5	Pearson Corr.	0.006	-0.105	-0.195
		Sig.(2-tailed)	0.970	0.497	0.205
	HX	Pearson Corr.	-0.400**	-0.077	-0.234
		Sig.(2-tailed)	0.007	0.621	0.127
Force-time-integral	MH1	Pearson Corr.	0.135	0.040	-0.059
		Sig.(2-tailed)	0.381	0.798	0.706
	MH2	Pearson Corr.	-0.122	-0.294	0.064
		Sig.(2-tailed)	0.431	0.053	0.680
	MH3	Pearson Corr.	0.078	-0.057	0.265
		Sig.(2-tailed)	0.613	0.712	0.082
	MH4	Pearson Corr.	0.053	-0.195	0.055
		Sig.(2-tailed)	0.732	0.204	0.721
	MH5	Pearson Corr.	0.096	-0.133	-0.141
		Sig.(2-tailed)	0.535	0.391	0.363
	HX	Pearson Corr.	-0.291	-0.028	-0.162
		Sig.(2-tailed)	0.055	0.859	0.292

MH = metatarsal, HX = hallux, *Correlation significant at 0.05 level, **Correlation significant at 0.01 level

APPENDIX P

CORRELATION OF PEAK PRESSURE WITH FIRST METATARSOPHALANGEAL JOINT RANGE OF MOTION AT PRE- AND 24-MONTHS POST-OPERATION IN HALLUX VALGUS GROUP

		N=44	Pre-operation			Post-operation		
			ROM	DF	PF	ROM	DF	PF
Peak pressure	MH1	Pearson Corr.	0.393**	0.397**	0.062	-0.008	-0.012	-0.012
		Sig.(2-tailed)	0.008	0.008	0.689	0.958	0.938	0.938
	MH2	Pearson Corr.	0.010	0.039	-0.064	0.280	0.218	0.228
		Sig.(2-tailed)	0.951	0.804	0.680	0.065	0.155	0.137
	MH3	Pearson Corr.	-0.219	-0.193	-0.096	0.060	0.046	-0.003
		Sig.(2-tailed)	0.153	0.209	0.536	0.698	0.769	0.984
	MH4	Pearson Corr.	0.196	0.271	-0.054	-0.140	-0.233	0.157
		Sig.(2-tailed)	0.203	0.074	0.727	0.363	0.129	0.309
	MH5	Pearson Corr.	-0.074	-0.279	0.241	-0.141	-0.193	0.071
		Sig.(2-tailed)	0.632	0.066	0.115	0.361	0.209	0.649
	HX	Pearson Corr.	-0.039	-0.086	0.056	0.153	0.183	0.196
		Sig.(2-tailed)	0.803	0.579	0.720	0.323	0.484	0.202
Pressure-time-integral	MH1	Pearson Corr.	0.318*	0.435**	-0.102	-0.011	-0.022	0.001
		Sig.(2-tailed)	0.036	0.003	0.510	0.943	0.887	0.996
	MH2	Pearson Corr.	-0.125	0.066	-0.302*	0.300*	0.242	0.226
		Sig.(2-tailed)	0.420	0.672	0.047	0.048	0.113	0.141
	MH3	Pearson Corr.	-0.277	-0.132	-0.262	0.046	0.002	0.085
		Sig.(2-tailed)	0.069	0.392	0.086	0.766	0.990	0.584
	MH4	Pearson Corr.	0.075	-0.029	0.158	-0.134	-0.221	0.155
		Sig.(2-tailed)	0.628	0.854	0.306	0.387	0.149	0.315
	MH5	Pearson Corr.	-0.106	-0.238	0.138	-0.150	-0.199	0.062
		Sig.(2-tailed)	0.493	0.119	0.371	0.332	0.194	0.690
	HX	Pearson Corr.	-0.025	0.031	-0.089	0.146	0.093	0.207
		Sig.(2-tailed)	0.872	0.842	0.567	0.345	0.548	0.178

Contact time	MH1	Pearson Corr.	0.089	0.214	-0.148	0.099	0.081	0.051
		Sig.(2-tailed)	0.568	0.163	0.338	0.522	0.600	0.744
	MH2	Pearson Corr.	-0.040	-0.025	-0.035	0.126	0.114	0.037
		Sig.(2-tailed)	0.795	0.874	0.824	0.416	0.460	0.812
	MH3	Pearson Corr.	-0.238	-0.195	-0.105	0.020	0.022	-0.025
		Sig.(2-tailed)	0.120	0.205	0.498	0.899	0.889	0.870
	MH4	Pearson Corr.	-0.188	-0.071	-0.195	-0.134	-0.111	-0.128
		Sig.(2-tailed)	0.223	0.645	0.204	0.385	0.474	0.406
	MH5	Pearson Corr.	0.046	-0.11	0.082	-0.063	-0.019	-0.146
		Sig.(2-tailed)	0.765	0.942	0.598	0.685	0.900	0.343
	HX	Pearson Corr.	0.073	0.018	0.096	0.098	-0.004	0.290
		Sig.(2-tailed)	0.639	0.908	0.537	0.526	0.981	0.056
Maximum force	MH1	Pearson Corr.	0.434**	0.473**	0.066	-0.055	-0.027	-0.091
		Sig.(2-tailed)	0.003	0.001	0.673	0.724	0.860	0.555
	MH2	Pearson Corr.	0.149	0.019	0.213	0.075	0.074	0.043
		Sig.(2-tailed)	0.334	0.903	0.166	0.628	0.631	0.781
	MH3	Pearson Corr.	-0.045	-0.099	0.083	-0.131	-0.037	-0.263
		Sig.(2-tailed)	0.771	0.524	0.594	0.396	0.813	0.085
	MH4	Pearson Corr.	-0.336*	-0.299*	-0.106	-0.231	-0.233	-0.072
		Sig.(2-tailed)	0.026	0.049	0.492	0.131	0.128	0.642
	MH5	Pearson Corr.	-0.181	-0.267	0.044	-0.173	-0.226	0.065
		Sig.(2-tailed)	0.241	0.079	0.779	0.262	0.140	0.673
	HX	Pearson Corr.	-0.33	0.007	-0.066	0.173	0.149	0.048
		Sig.(2-tailed)	0.832	0.963	0.672	0.375	0.336	0.756
Force-time-integral	MH1	Pearson Corr.	0.357*	0.658**	-0.188	0.001	0.006	-0.022
		Sig.(2-tailed)	0.018	<0.001	0.222	0.992	0.969	0.887
	MH2	Pearson Corr.	0.077	0.187	-0.128	0.129	0.126	0.065
		Sig.(2-tailed)	0.620	0.224	0.408	0.402	0.417	0.673
	MH3	Pearson Corr.	-0.168	-0.055	-0.170	-0.105	-0.044	-0.168
		Sig.(2-tailed)	0.275	0.7245	0.269	0.498	0.776	0.274
	MH4	Pearson Corr.	-0.400**	-0.249	-0.278	-0.246	-0.257	-0.060
		Sig.(2-tailed)	0.007	0.103	0.068	0.108	0.093	0.699
	MH5	Pearson Corr.	-0.179	-0.207	-0.026	-0.200	-0.247	0.039
		Sig.(2-tailed)	0.246	0.178	0.869	0.192	0.106	0.801
	HX	Pearson Corr.	-0.073	0.078	-0.223	0.133	0.124	0.085
		Sig.(2-tailed)	0.635	0.617	0.145	0.388	0.4234	0.582

MH = metatarsal, HX = hallux, *Correlation significant at 0.05 level, **Correlation significant at 0.01 level

APPENDIX Q

PUBLICATIONS, CONFERENCE PRESENTATIONS AND GRANTS

A. Publications

Throughout the doctoral studies a number of manuscripts were accepted for publication in international scientific/medical journals.

Bryant, A., Singer, K., and Tinley, P. (1999). Comparison of the reliability of plantar pressure measurements using the two-step and midgait methods of data collection. Foot & Ankle International. 20(10), 646-650.

Bryant, A., Tinley, P., and Singer. K. (1999). Normal values of plantar pressure measurements using the EMED-SF system. Journal of American Podiatric Medical Association. 90(6), 295-299.

Bryant, A., Tinley, P., and Singer, K. (2000). A comparison of radiographic measurements in normal, hallux valgus and hallux limitus feet. The Journal of Foot and Ankle Surgery. 39(1), 39-43.

Bryant, A., Tinley, P., and Singer, K. (1999). Plantar pressure in normal, hallux valgus and hallux limitus feet. The Foot. 9(3), 115-119.

Bryant, A., Tinley, P., and Singer, K. (2000). Radiographic measurements and plantar pressure distribution in normal, hallux valgus and hallux limitus feet. The Foot. 10(1), 18-22.

B. Conference Presentations

Presentations based on research data related to this doctoral thesis were presented at State professional and academic conferences.

Bryant, A. (1998). Radiographic differences between normal, hallux valgus and hallux limitus feet. Annual, Podiatry Association (WA) State Conference. Perth, October.

Bryant, A., Singer, K., and Tinley, P. (1998). Intra-subject reliability of selected plantar pressure measurements. The Mark Liveris Health Sciences Research Student Seminar. Curtin University, Perth, 3 December. (Poster presentation).

C. Grants awarded

In 1998 the Podiatrists Registration Board of Western Australia awarded a grant of $6,295 to help facilitate the purchase of computer hardware donated to Curtin University of Technology and used during the doctoral study, and funds to attend the VI EMED Scientific Meeting, in Brisbane, 8-13 August, 1998.

Also in 1998, Novel gmbh, manufacturers of the EMED-SF system, supplied a computer 'hard-lock' device valued at $10,000 for a 12-month period. This device allowed the EMED software to run on a personal computer, distant from that situated in the Department of Podiatry.