PREDICTORS OF HALLUX VALGUS:

A STUDY OF HERITABILITY.

A thesis submitted for the degree of Doctor of

Philosophy

University of Leicester.

S.K. Spooner, BSc., SRCh.

September 1997

ACKNOWLEDGEMENTS

I should like to express sincere gratitude to my supervisory team for their invaluable knowledge and eternal patience:

Dr. J. A. Campbell

Dr. T. E. Kilmartin

Dr. B. Kyriacou

Mrs. L. M. Merriman

I should also like to thank all of the families who gave their time as subjects, without whom the study could not have been carried out.

This work is dedicated to my mother and father, in gratitude of their love, support and understanding.

ABSTRACT

Hallux valgus is a complex progressive foot deformity of uncertain aetiology. The disorder is characterised by a lateral deviation of the hallux at the first metatarsophalangeal joint; an angle ≥ 15° is considered as clinical hallux valgus. A model that predicts first metatarsophalangeal joint angle and thus, hallux valgus is potentially very useful; enabling the clinician to identify individuals at risk of developing the disorder and to predict prognosis. The aim of this study is to develop such a model.

The literature relating to hallux valgus identifies eight potential aetiological factors of hallux valgus. The scientific evidence presented in support of these suspected aetiological factors, and the theories of pathology of hallux valgus in association with these factors were critically evaluated by a review of the literature. Methods to evaluate the significance of these factors in hallux valgus were identified and appraised. These methods were applied to a large sample of genetically related individuals.

The genetic and environmental influences affecting first metatarsophalangeal joint angle, pes planus, metatarsal formula, digital formula and first ray neutral position were explored through the statistical analysis of the data obtained from the sample. The results of analyses suggest that all of these variables are gender influenced, multifactorial traits.

Further analysis of a subset of data generated a statistical model that relates the degree of hallux deviation at the first metatarsophalangeal joint (and thus, the degree of hallux valgus) to clinically measurable predictor variables. A further subset of data was applied to test the model. The model was found to accurately predict first metatarsophalangeal joint angle in 92% of cases. Application of the model allows the clinician to evaluate an individual's risk of developing hallux valgus enabling accurate prognosis. Recommendations for achieving improved prognosis and the implications for future research are proposed.

DISCLAIMER

This thesis describes original work by Simon Kenneth Spooner which was completed during the period of registration. No part of this work has been submitted for a higher degree at this or any other university.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I

INTRODUCTION

"*There are many maladies of unknown etiologies* [sic] *involving the foot which can be and are treated with adequate results. Yet when the etiology is known, the information can be used to improve the present mode of treatment and help to reduce or even eliminate its incidence"* (Janis and Donick 1975).

Hallux valgus is a complex, progressive foot deformity of unknown actiology. The pathological changes in hallux valgus are primarily exhibited as lateral deviation of the hallux at the first metatarsophalangeal joint (1st MPJ); but as the disorder progresses it may involve, if not directly deform, the whole forefoot (Piggott 1960).

Kilmartin et al. (1991), aware of the significance of the deformity, maintained that: *"Hallux valgus is probably responsible for more pathology than any other single abnormality of the forefoot".* Great amounts of time and resources are spent on the treatment of hallux valgus, its related soft tissue lesions and associated forefoot deformities[1].

The abundance of research stimulated by hallux valgus reflects the importance of the condition. However, despite much being written on the subject of hallux valgus, a great deal of uncertainty remains. Little explanation as to definitive aetiology has been provided by the many published investigative studies. Modern texts exhibit a confused state; merely listing proposed predisposing factors, in what seems to be an unspecified order. No adequate methods of calculating an individual's risk of developing hallux valgus, or of predicting the prognosis of the condition have been advanced for use in clinical practice.

[1] An attempt to quantify the time and resources spent on the treatment of hallux valgus within the NHS Trusts of the UK was made by the author. However, at the time of this study, the audit procedures employed by all of the NHS Trusts contacted by the author did not provide a break-down of costing for the treatment of specific foot deformities. Therefore, quantification was not possible.

Kilmartin and Wallace (1993) believed that the uncertainty of actiology and the inability to identify individuals at risk of hallux valgus, has hampered the treatment of the condition; they stated that:

"While it cannot be certain that understanding the cause of hallux valgus will inevitably lead to a more effective treatment of the condition, surgical treatment of hallux valgus has usually been undertaken when symptoms develop in the late stages of the condition, the outcome is variable not least because at that stage the deformity is more complicated. Identifying the aetiology may allow earlier, perhaps even conservative treatment to be instigated, prior to the development of first metatarsophalangeal joint osteoarthrosis and involvement of the whole forefoot".

A model that relates the degree of lateral hallux deviation to clinically measurable variables appears to be potentially very useful, providing the clinician with a method of identifying individuals at risk of developing hallux valgus and predicting the prognosis of the deformity. This should allow an earlier instigation of treatment, perhaps preventing the development of osteoarthritic changes at the 1st MPJ and deformity of the whole forefoot. Moreover, if individuals at risk of hallux valgus can be identified prior to the onset of the condition, it may be possible to initiate prophylaxis. Thus, the incidence of the deformity may be reduced. The study described in this thesis was aimed at the development of such a model.

To achieve the aim of the study several key objectives were defined:

(i) review critically the literature concerning hallux valgus;

(ii) identify potential aetiological factors of hallux valgus from the literature;

(iii) propose a descriptive clinical model that relates hallux valgus to its potential aetiological factors;

(iv) identify, evaluate and apply methods of collection and quantification of clinical measurements of hallux valgus and its potential aetiological factors to obtain data from a sample;

(v) apply appropriate statistical analyses to the data to quantify genetic and environmental influences in hallux valgus and its potential aetiological factors;

(vi) apply appropriate statistical analyses to the data to evaluate the interrelationships between factors and the individual significance of each factor in hallux valgus;

(vii) refine the descriptive model to predictive mathematical form by incorporating the information obtained from the data analyses;

(viii) test the refined model's ability to predict hallux valgus;

(ix) provide discussion and interpretation of the results.

By critical analysis of the literature concerning hallux valgus, this thesis first defines hallux valgus (Chapter II, Section 2.1) and then draws together and evaluates the existing knowledge regarding the onset, prevalence and aetiology of the condition. Using information gleaned from this review of literature, several proposed aetiological factors of hallux valgus are selected for further investigation (Chapter II).

Methods to collect and quantify clinical measurements of hallux valgus and the proposed aetiological factors are identified, evaluated and selected for use. The rationale for selection of the measurement techniques is discussed (Chapter III, Section 3.3). Before the methods of clinical assessment selected for use in the study could be considered reliable techniques on which to base conclusions of the study upon, the reproducibility of measurements obtained using these techniques had to be analysed. A series of experiments was designed and carried out to test the between-day intra-observer error of the measurement techniques (Chapter III, Section 3.3).

Chapter III, Section 3.2 proposes a descriptive clinical model that relates the degree of lateral deviation of the hallux at the 1st MPJ to several factors proposed as significant in the aetiology of hallux valgus. The mathematical development of this model, leading to specific parameter values is presented in Chapter IV.

Genetic inheritance has long been considered important in the aetiology of hallux valgus but little empirical evidence has been provided in support of this theory. Despite the general acceptance that hallux valgus per se could be inherited, the possibility that other aetiological factors may be genetically influenced has not been considered. Direct measurements of hallux valgus and a range of proposed aetiological factors made on a large number of genetically related subjects are used to quantify genetic and environmental influences (Chapter IV, Section 4.6). The clinical model is refined to incorporate the information obtained from these analyses.

The interrelationships between factors and the individual significance of each factor in hallux deviation are tested using multiple linear regression analysis to a subset of the data (Chapter IV, Section 4.7). The clinical model is further refined to produce a predictive mathematical model (Chapter IV, Section 4.7).

A further subset of data are applied to test the model's ability to predict hallux valgus (Chapter IV, Section 4.8).

Chapter V provides discussion and interpretation of the results. The chapter is divided into two parts: Part I (Sections 5.2- 5.7) presents considerations of the results of the genetic analyses and estimations of heritability. Part II (Sections 5.8-5.15) addresses the predictors of 1st MPJ angle and proposes theoretical mechanisms of hallux valgus formation in association with these factors.

The final chapter (VI) first draws together the findings of the study, deriving conclusions from the results obtained (Section 6.2). Following this summation, the clinical implications of the study are defined and recommendations for improvements to clinical practice are made (Section 6.3). Finally, consideration is given to future research regarding hallux valgus; implications and directions for this research are outlined (Section 6.4).

Chapter II

REVIEW OF LITERATURE

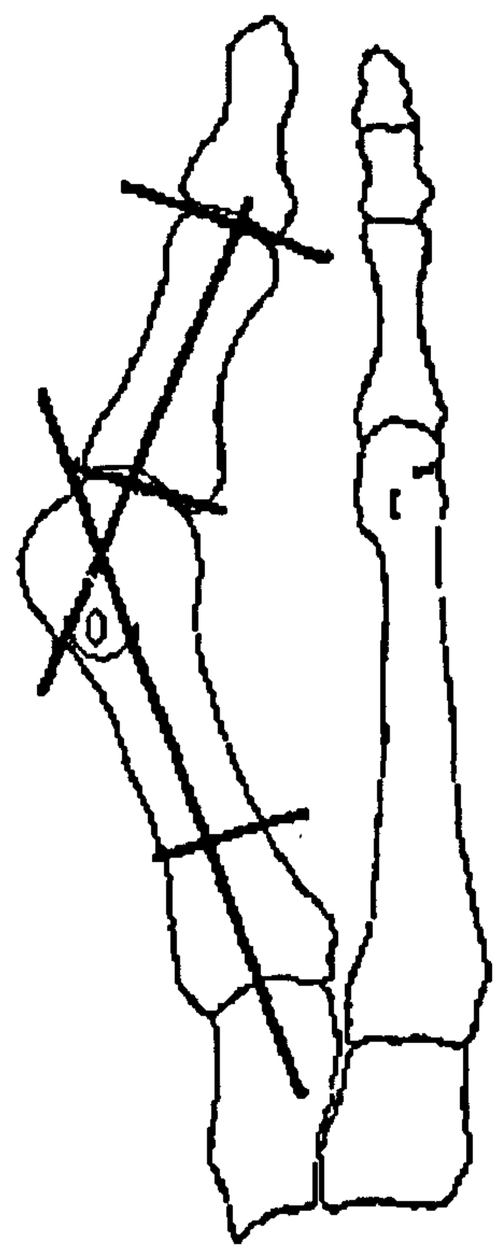
2.1 Definition of Hallux Valgus

The term bunion is commonly, and inappropriately, used to describe hallux valgus. This term lacks clarity, being applied synonymously to describe bursal inflammation over the 1st MPJ, the bony medial eminence associated with hallux valgus and to any painful condition or deformity of the 1st MPJ. Durlacher (1845), aware of the misuse of the term, suggested: "*The word bunion, which has been almost indiscriminately applied by the public to any hard and painful tumour, or corn of the feet, should be restricted in its use to designate an enlargement over the first joint of the great or little toe, produced by pressure or by some other cause, effecting a change in the position of the joint.*" Clearly Durlacher (1845) identified the need for a more precise definition of the condition, but failed to recognise the primary deformity.

Kelikian (1965) states that the term hallux valgus was introduced into the literature by Hueter (1871) to describe "*an abduction contracture*" of the great toe. The disorder is characterised by a lateral deviation of the proximal phalanx of the hallux; however, this is just one component of the syndrome. Stamm (1957) provided a clearer definition: "*a complex progressive deformity affecting the forefoot in which lateral deviation of the great toe is the most obvious feature*". This syndrome may include the following: contracture of the lateral joint capsule, attenuation of the medial joint capsule, a medial eminence on the metatarsal head, axial rotation of the hallux, subluxation of the sesamoids, and medial deviation of the first metatarsal (Mann 1986), overriding of the second toe by the hallux, overriding of the lateral toes, metatarsalgia, hammer and claw deformities of the lateral toes and bunionette of the fifth metatarsal. However, many otherwise normal individuals exhibit lateral deviation of the hallux on its metatarsal to a greater or lesser degree (Goldner and Gaines 1976); thus, it is essential to differentiate between normality and abnormality.

The degree of lateral deviation of the hallux on its metatarsal would appear to provide an objective method to make the distinction between hallux valgus and normality (Kilmartin and Bishop 1988). In an attempt to make this differentiation, Hardy and Clapham (1951) used radiographic assessment of the 1st MPJ angle, the angle formed between the longitudinal bisection of the first metatarsal and its proximal phalanx (Figure 2.1). They reported a mean angle in normal adolescents of 12.0° and in normal adults of 15.7°.

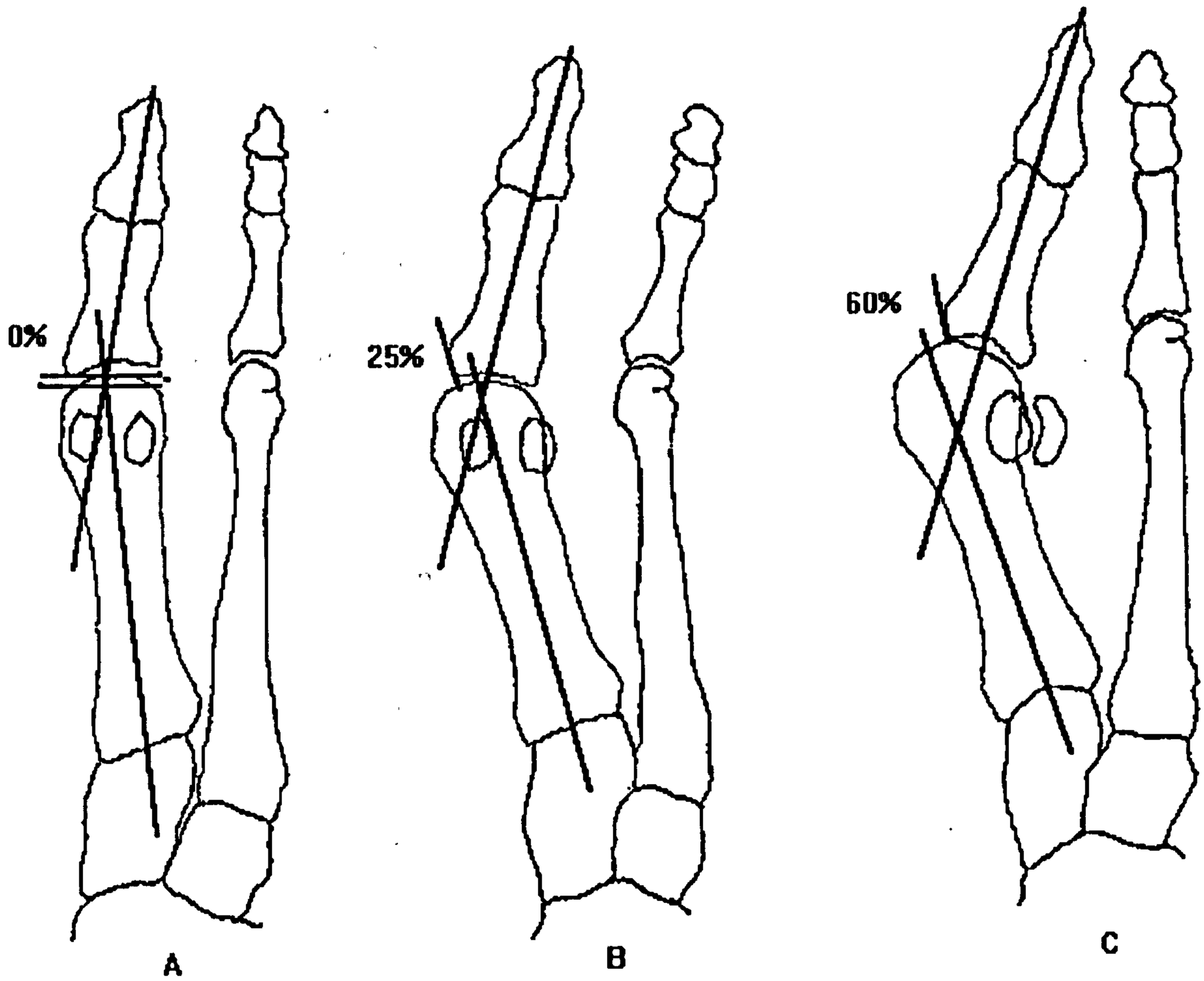
Figure 2.1: The angle θ denotes the first metatarsophalangeal joint angle: the angle formed between a longitudinal bisection of the first metatarsal and its proximal phalanx.



Piggott (1960) disputed the use of the measurement of 1st MPJ joint angles to detect normality from abnormality. Basing his classification on 1st MPJ congruency, he suggested that joints with large 1st MPJ angles may be congruous as in the normal joint. Lateral deviation of the hallux in this type of joint, being due to an exaggeration of the normal tilting, of the articular surface, of the base of the

proximal phalanx and the metatarsal head. The lateral deviation does not progress and is, therefore, not a pathological condition. Piggott (1960) defined three distinct radiological groups: congruous, deviated and subluxed, based on the percentage of the medial side of the metatarsal head exposed, due to lateral movement of the phalanx (Figure 2.2). If the joint is congruous, progression is unlikely and is, therefore, not classed as pathology by Piggott's definition. However, if the joint is subluxed, progression is likely, and if it is deviated, some, but not all, will progress.

Figure 2.2: Classification of hallux valgus based on the percentage of metatarsophalangeal joint exposure. A: Congruous, B: Congruous, phalanx deviated, C: Subluxed.



Seeking a clinical alternative to the X-ray classification of hallux valgus described by Hardy and Clapham (1951), Kilmartin and Bishop (1988) used goniometric measurements of the 1st MPJ angle to define hallux valgus. 1st MPJ angles measured clinically to be ≥15° were considered as abnormal. They concluded that clinical measurements of the deformity made using this technique provided a viable alternative to X-ray evaluation. This statement was later substantiated by Kilmartin and Wallace (1992) when they identified a strong linear relationship ($r=0.75$, $r^2=0.56$, $n=58$) between goniometric and X-ray measurements of 1st MPJ angle.

Hallux valgus is a complex progressive deformity. The point at which normality becomes pathology is likely to vary between individuals. Since prognosis cannot be predicted, the deviation of the hallux on its metatarsal cannot be applied in isolation to delineate abnormality from normality. Congruency of the 1st MPJ is more predictive of progression of the deformity but the accuracy of radiographic assessment of joint congruency is debatable. Although Piggott (1960) contested the views of Hardy and Clapham (1951), and based his criteria for distinguishing between normal and abnormal on joint congruency, he maintained that a 1st MPJ angle of 15° was a good, if somewhat artificial delineation.

Since X-ray evaluation was not used within this study, the clinical definition provided by Kilmartin and Bishop (1988) was adopted; 1st MPJ angles measured clinically using a finger goniometer to be ≥15° were considered as abnormal and thus, hallux valgus. 1st MPJ angles measured clinically to be <15° were considered as being within normal limits.

2.2 Onset of Hallux Valgus

The onset of hallux valgus varies. It may be congenital. It may manifest during adolescence or, later, in adult life. Congenital hallux valgus is rare. However, a few isolated cases of the condition are reported (Thul, Stone and Gilarski 1985). Mahan and Jacko (1991) suggest that juvenile hallux valgus most commonly presents between the ages of 11 and 14 years, but provide little evidence to substantiate this conjecture. When hallux valgus manifests in adult life, even greater uncertainty exists concerning the prevalence since, commonly, no distinction is made concerning time of onset of the condition in epidemiological surveys.

Evidently, some individuals display hallux valgus from birth while some develop it in their adolescence and some in adulthood. Why do certain individuals display this period of latency while others do not? Lake (1952) suggested that hallux valgus observed in juveniles was probably due to different actiology from the type observed in older individuals, but provided no support for this conjecture. Neale et al. (1985) maintained that delineation may exist within the group of cited predisposing factors. They suggested that there are both contributory factors and exciting factors. Contributory factors, e.g. excessive weightbearing due to obesity or pregnancy, may place the foot under increased strain, but this may not affect the structurally stable foot. In the presence of exciting factors, however, that render the foot structurally unstable, e.g. hypermobility of the forefoot associated with abnormal rearfoot pronation, the contributory factors may then predispose to both the aetiology and the symptoms. Thus, it is only when both the contributory and exciting factors are present that the condition develops. Again, the authors provided no scientific evidence in support of this theory.

Hallux valgus is commonly bilateral, affecting both feet (Hardy and Clapham 1951). However, the degree of the deformity is often asymmetrical between right and left feet. Indeed, unilateral hallux valgus is frequently observed in clinical practice. The use of 1st MPJ angles as an artificial delineation between normality and pathology (see Section 2.1), may partly explain this. Take for example, an individual who exhibits a 1st MPJ angle of 14° on their left foot and 15° on their right foot. Clearly, little difference exists between the two feet. However, the degree of deviation of the hallux on the left foot may be considered within normal limits, by many definitions, whereas the deviation of the right hallux may be classified as abnormal, and thus pathological. Often, however, far greater difference exists between the left and right feet of individuals. Kilmartin, Barrington and Wallace (1991) suggested that in such cases the unaffected foot is at risk of developing the deformity because hallux valgus is usually bilateral. However, this does not explain why one foot often exhibits an earlier onset of the condition or progresses more rapidly. Do distinct differences exist between the right and left feet of individuals displaying unilateral hallux valgus?

2.3 The Prevalence of Hallux Valgus

Greenberg et al. (1963) in a study of 1,878 New York school children noted a prevalence of bunions and incipient bunions in the order of 6%. Sabbann (1965) reported a prevalence of bunions of 1.75% in a survey of 1,370 children under the age of 15 years. These earlier authors do not define the term bunion and so few conclusions can be drawn from these studies. In a survey of joint mobility and foot problems of 191 Australian children, Marr and D'Abrera (1985) noted a prevalence of hallux valgus of 11.8% in females, compared to only 3.5% in males. However, the authors reported no criteria for diagnosis of the condition. More recently, Kilmartin and Wallace (1990) reported a prevalence of 2.3% of 6,400 nine-year-old school children. The study of Kilmartin and Wallace provided full details of the criteria used for diagnosis of the condition:

1. A hallux abductus angle, measured clinically using a finger goniometer, in excess of 15°.
2. Medial propulsion from the hallux.
3. Clinically palpable osteophytic thickening of the joint.

Adult and geriatric foot surveys have suggested a higher prevalence of the condition: Merrill, Frankson and Tarara (1967) noted a prevalence of approximately 24% in their study of 1,011 nursing home patients of 60 years old and more, in Minnesota. Approximately 4% of subjects exhibited unilateral hallux valgus of the right foot, 2% of the left foot and approximately 17% bilateral. 19% of the affected subjects were male and 81% were female. Schnitzer and Hoeffler (1974), in a study of 14,470 male American Navy recruits, reported a prevalence of 19.4%. More recently Brodie et al. (1988) carried out a survey of chiropody patients in the Wessex region. They reported that hallux valgus was almost three times as prevalent in females as in males until the age of 64 years, when the prevalence between genders converged. However, this gap again widened at age 75 years and older. The results of the Wessex foot health survey are summarised in Table 2.1.

Table 2.1: A summation of the results of the Wessex foot health survey (1988).

AGE GROUP	5-14	15-24	25-44	45-64	65-74	75+
PREVELENCE MALE (%)	0	2	3	10	15	20
PREVELENCE FEMALE (%)	10	5	10	30	20	55

In reviewing the literature concerning the prevalence of hallux valgus it may be concluded that:

i. The prevalence of hallux valgus appears to increase, with age.

ii. Hallux valgus may be more common in females.

2.4 The Aetiology of Hallux Valgus

The literature concerning the aetiology of hallux valgus is extensive but is in general not backed by systematic research. There are therefore many theories but little has been substantiated. Where investigative studies have been carried out they have not defined a common aetiology. Although some testing of the interrelationships between suspected causative factors has been conducted, there has been no ranking of the aetiological theories by significance. This section will summarise the evidence presented in the literature concerning the various theories of aetiology.

2.4.1 Survey of Contemporary Textbooks

Perhaps an appropriate starting point for this review is a summary of the aetiological factors currently believed to be significant in the development of hallux valgus, as listed by contemporary textbooks. Textbooks provide only secondary sources of information. However, their use appears justified here, in simply highlighting some different theories of aetiology. Such theories are commonly and inappropriately reported as facts, when they are at best, only conjectures, representing current knowledge. Moreover, a review of this nature underlines the inconsistency of terminology and the confusion associated with the condition. A cross-section of podiatric, orthopaedic and general medical textbooks were reviewed. All of the books chosen were published between 1982 and 1993 to achieve a contemporary viewpoint. The results of this survey are presented in Table 2.2. Aetiological factors are listed in the order that they appear in the texts.

Table 2.2: Aetiological factors believed to be significant in the development of hallux valgus as listed in contemporary textbooks (1982-1993).

AUTHOR / BOOK TITLE / YEAR OF PUBLICATION	AETIOLOGICAL FACTORS LISTED
Apley and Solomon: "Apleys System of Orthopaedics and Fractures" 1982	1) Metatarsus primus varus 2) Congenital 3) Acquired 4) Shoes
Hughes: "Footwear and Footcare for Disabled Children" 1982	1) Pes planus 2) Stills disease
Klenerman: "The Foot and its Disorders" 1982	1) Hereditary 2) Metatarsus primus varus 3) Muscle imbalance 4) Foot pronation 5) Shoes 6) Rheumatoid Arthritis 7) Congenital 8) Obesity 9) Tight Achilles tendon 10) Os Intermetatarsum 11) Length of metatarsal 12) Iatrogenic
Cailliet: "Foot and Ankle Pain" 1983	1) Congenital 2) Metatarsal length 3) Metatarsus primus varus 4) Muscle imbalance 5) Shoes 6) Excess body weight
Harris: "Post Graduate Textbook of Orthopaedics" 1983	1) Hereditary 2) Metatarsus primus varus 3) Shoes 4) Weakness in stabilizing structures

Hughes: "Footwear and Footcare for Adults" 1983	1) Hereditary 2) Short 1st Metatarsal 3) High 1st intermetatarsal angle 4) Gender 5) Footwear 6) Bone shape
Duckworth: "Lecture notes on orthopaedics and fractures" 1984	1) Gender
Cyriax: "Textbook of orthopaedic medicine" 1985	1) Shoes
Miller and Miller: " Orthopaedics and Accidents Illustrated" 1985	1) Congenital 2) Acquired 3) Shoes
Tachdjian: "The Child's Foot" 1985	1) Metatarsus Primus Varus 2) Cerebral Palsy 3) Rheumatoid Arthritis
Mann: "Surgery of the Foot" 1986	1) Shoes 2) Hereditary 3) Pes planus 4) Metatarsus primus varus 5) Metatarsal length 6) Iatrogenic, secondary to amputation of second toe 7) Cystic degeneration of medial joint capsule resulting in a ganglion 8) Contracture of Achilles tendon 9) Neuromuscular/Stroke 10) Idiopathic 11) Joint hyperelasticity
Rodrigo: "Orthopaedic Surgery- Basic Science and Clinical Science" 1986	1) Shoes
Muckle: "An Outline of Orthopaedic Practice" 1986	1) Fall of transverse arch

Magee: "Orthopaedic Physical Assessment" 1987	1) Hereditary 2) Shoes 3) Hosiery 4) Metatarsus primus varus
Neale and Adams: "Common Foot Disorders" 1985	1) Metatarsus primus varus 2) Metatarsus adducts
Helal and Wilson: "The Foot" 1988	1) Shoes 2) High intermetatarsal angle 3) Age 4) Hereditary 5) Gender 6) Stability of the 1st ray 7) Metatarsus primus varus 8) Muscle imbalance 9) Other foot deformities 10) Bowstringing of extrinsic tendons 11) Weakness of medial supporting structures
Paton: "Fractures and Orthopaedics" 1988	1) Inherited 2) Torsional shape of legs 3) Forefoot pronation 4) Metatarsus primus varus
Seibal: "Foot Function" 1988	1) 1st ray hypermobility, secondary to subtalar joint pronation 2) Forefoot adductus
Dandy: "Essential Orthopaedics and Traumatology" 1989	1) Hereditary
Gates and Mooar: "Orthopaedic and Sports Medicine for Nurses" 1989	1) Hereditary 2) Secondary to metatarsus primus varus 3) Muscle imbalance 4) Foot pronation 5) Shoes

Adams and Hamblen: "An Outline of Orthopaedics" 1990	1) Hereditary 2) Shoes
DeValentine: "Foot and ankle disorders in children" 1992	1) Malposition of 1st metatarsophalangeal joint 2) Severe flatfoot 3) Equinus 4) Hereditary 5) Limb bud deficiency 6) Footwear 7) Metatarsus primus varus 8) Atavism 9) Metatarsal length 10) Metatarsal head shape
Cyriax and Cyriax: "Cyriaxs Illustrated Manual of Orthopaedic Medicine"1993	1) Pronation 2) Shoes

The most commonly cited aetiological factor in the textbooks reviewed was footwear. 65% of texts acknowledged that footwear may play a role in the deformity. Metatarsus primus varus / high intermetatarsal angle was reported as an actiological factor in 56% of the texts. Of the twenty-three books reviewed, 11 (47%) of them mentioned inheritance as an aetiological factor. Closely linked with this is gender, reported in 13% of books reviewed. Approximately 35% of the texts reported pes planus (pronation) as a factor. The length of the first metatarsal was considered significant in 21% of the books, as was muscular imbalance and the congenital manifestation of the condition. Equinus of the foot was reported in 13% of texts. Metatarsal head shape and rheumatoid arthritis were reported in approximately 9% of the books reviewed. Other factors including first ray position, neuromuscular conditions, body mass, previous foot surgery, age, other foot deformities, atavistic reversion and the shape of legs were all reported, but less frequently.

The aim of this study was to provide a model that relates the degree of hallux deviation to clinically measurable variables, providing the clinician with a method of identifying individuals at risk of developing hallux valgus and predicting prognosis. As the desired outcome is a widely applicable clinical model that accurately predicts hallux deviation using only a few simple clinical measurements, the following factors were selected for further study: genetic inheritance, gender, age, footwear, metatarsal length, digital length, pes planus / pronation and first ray position. Clearly, the literature concerning these factors required an in depth review.

It may have been possible to develop a model that relates the degree of hallux deviation to all of the factors listed in Table 2.2. However, the application of such a model in the clinical environment would be impracticable and limited in its application since a large number of measurements, requiring specialised, expensive equipment, would be needed.

2.4.2 A Critical Review of the Aetiology of Hallux Valgus

This section reviews the literature concerning the aetiological factors of hallux valgus under investigation, critically evaluates the scientific evidence presented in support of these suspected aetiological factors, and investigates the theories of the pathology of hallux valgus in association with these factors.

2.4.2.1 Genetic Inheritance

The theory of genetic inheritance as an aetiological factor in hallux valgus has been proposed from patterns of aggregation of the deformity in families, from the preponderance of affected females, and from the prevalence of the condition in barefooted communities. However, little empirical evidence has supported the existence of such a relationship.

To the author's knowledge, only one study supports the hypothesis that hallux valgus is due to the expression of a single Mendelian gene. Johnston (1956) proposed that the pattern of inheritance of hallux valgus was autosomal dominant with incomplete penetrance, following his study of

oneseven-generation family (101 subjects), exhibiting hallux valgus and pes planus. The results of Johnston's study are summarised in Table 2.3.

Table 2.3: A summation of the results of Johnston (1956).

DEFORMITY	MALE	FEMALE
Hallux Valgus	10	10
Pes Planus	13	1
Hallux Valgus & Pes Planus	6	1
Unaffected	24	36

Hallux valgus was present in every generation of the family. Except in two cases, all of the offspring of the affected parents exhibited the condition. The children of the two unaffected offspring were also affected.

Johnston's study provides the most conclusive evidence to date, in support of the genetic hypothesis. However, he did not define his criteria for diagnosis of the conditions. Furthermore, Johnston (1956) studied only one pedigree and did not present the results of any segregation analysis; thus, any conclusions drawn from this study should only be applied to the wider population with extreme caution.

Many authors have used the presence of a family history of the deformity to substantiate their conjectures that the deformity displays the characteristics of an inherited trait. Hardy and Clapham (1951) reported a positive family history in 63% of 91 patients in contrast to their controls with unaffected feet who displayed a positive family history of only 1%. Of those that reported a positive family history, 77% implicated their mother and 16% their father. Mitchell et al. (1958) noted that 58% of patients reviewed with hallux valgus provided a positive family history (although they did not specify the degree of deviation of the hallux considered abnormal). Glynn et al. (1980) reported a positive family history in 68% of 41 patients. Bonney and Macnab (1952) proposed that affected

subjects with a positive family history of hallux valgus displayed a premature onset of pain and deformity. Again, no criteria for diagnosis of the deformity were presented.

Kilmartin and Wallace (1990) in their study of 224 nine-year-old school children reported that every child with hallux valgus was found to have either a positive family history or a plantarflexed first ray (in excess of 2mm). Family history was collected by requesting the parents of the children to draw around their feet. Charting and measurement of the resultant outlines provided measures of 1st MPJ angles. The criterion for the diagnosis of hallux valgus was a 1st MPJ angle ≥15°. Of the unaffected children 13.5% had a positive family history and plantarflexed first rays. Kilmartin and Wallace (1990) suggested that although the relationship between first ray position and family history may appear weak, this percentage of the study population may progress to develop the deformity, given their findings. Further evidence for this is provided by the apparent increase in the prevalence of the deformity associated with increasing age. Clearly, a long term follow-up study is required to detect the accuracy of the observations presented. First ray neutral position was calculated from measurements of sagittal plane first ray motion obtained using the Kilmartin Sagittal Raynger, by subtracting the largest range of motion (whether it was plantarflexion or dorsiflexion) from the smallest. In doing this Kilmartin and Wallace (1990) failed to include a zero point between plantarflexion and dorsiflexion in their measurement scale. This produced an error in the measurement, with 1mm either side of zero excluded from the calculation: thus, the position of 2mm plantarflexed which Kilmartin and Wallace (1990) considered significant must be questioned. Furthermore, no tests of repeatability or validity were carried out on the methodology used to collect parental data.

Coughlin (1995) in a study of 45 juveniles reported a positive family history in 72% of subjects (28 females, 3 males). Of these subjects, 11 females reported a two generation history of mother to subject, and four females reported an unbroken four generation history of maternal great-grandmother to maternal grandmother to mother to subject. In 11 female subjects, a three generation history of maternal grandmother to mother to subject was reported; however, the mother was skipped (suggesting reduced penetrance) in two cases. Five females reported both mother and father affected. Two females reported only their father to be affected. Of the three affected males, two reported their mother to be

affected and one noted a three generation history of maternal grandmother to mother to subject. Coughlin (1995) also noted that the hallux valgus deformity was of greater severity in subjects with a positive family history. He concluded that hallux valgus may be familial, being transmitted from mother to offspring either in an X-linked dominant, autosomal dominant or polygenic manner.

Family history appears to provide strong support to the genetic hypothesis. However, a positive family history is not present in all cases of the deformity. Moreover, although hallux valgus appears to be familial, it may not be genetically determined. Indeed, the effects of shared environment may be important. The method used to obtain a family history is highly significant. Requesting patients to recall from memory if a history exists is obviously inaccurate, and results from such studies should be considered with caution. The method used by Kilmartin and Wallace (1990) is more accurate but the validity of this method is untested.

2.4.2.2 Gender

The apparent higher proportion of females affected by hallux valgus than males has led some authors to conclude that hallux valgus exhibits the characteristics of a sex-linked genetic trait (Heyling 1990, Coughlin 1995). However, it should be noted that sex-linked or X-linked traits may affect either gender (Cowell 1978). Indeed, Johnston (1956) identified an equal prevalence of hallux valgus in males and females within his study family. However, this is in marked contrast to the results of many other workers, who report a far greater prevalence among females than males.

Hawkins, Mitchell and Hendrick (1945) reviewed the results of bunionectomy procedures and noted that 88.3% of patients were female (age range=14-77 years , mean=42 years). Rogers and Joplin (1947) reported that 90% of their sample of 50 subjects was female. Gilmore and Bush (1957) screened 42 patients with hallux valgus and noted that of these only four were men (age range= 24-71 years, mean= 54 years). Gibson and Piggott (1962) in their follow-up study of first metatarsal osteotomies noted that of 88 patients only one was male. Carr and Boyd (1968) divided their subjects into an adolescent group (under 18 years) and an adult group (over 18 years). In the adolescent group 23 subjects were female and only five were male. Similar results were reported for the adult group that consisted of 23 females

and one male. Fitzgerald (1969) reviewed the long term results of arthrodesis of the 1st MPJ. Of the 100 subjects reviewed 85% were female.

It may be argued that the results of these earlier studies were obtained from biased populations since data was drawn from subjects who had previously undergone corrective hallux valgus surgery. Indeed, Bonney and Macnab (1952) contended that the increased preponderance of women presenting for surgery was probably due to increased pain arising from tighter shoes. Noting a marked difference in hallux valgus morbidity among the sexes, they concluded: "*While this preponderance is not fictitious, it is probably factitious, since men are more ready to wear shoes suitable to the shape of their foot.*" Craigmile (1953) added weight to this conjecture, noting that females were more likely to wear badly fitting shoes than their male counterparts, following her study of 12,765 school children. She reported that *"There is an increase in the number of children wearing badly fitting shoes with age, the senior girls* (age 12-15 years) *being far the worst group."*

Kilmartin and Wallace (1993) were clearly aware of the problems of results based on biased samples. In reviewing gender differences in hallux valgus they included only surveys that provided comprehensive information on gender and age and used no form of preselection based on gender. Table 2.4 summarises their results.

Table 2.4: Male:female ratio in published reports of hallux valgus surgery 1952-1992. After Kilmartin and Wallace (1993). Reproduced by kind permission of the authors.

AUTHOR	MALE	FEMALE	% FEMALE	AGE
Hardy, Clapham (1951)	3	88	96.7%	20-60
Bonney, Macnab (1952)	28	253	90.0%	Adults
Piggott (1960)	3	110	97.3%	<21
Merkel, Katoh (1983)	9	135	93.8%	12-75
Sherman, Douglas, Benson (1984)	0	35	100%	44-77
Meier, Kenzora (1985)	5	45	90.0%	13-69
Love, Whynot, Farine (1987)	0	44	100%	52-75
Wu (1987)	28	402	93.5%	10-90
Wanivenhaus, Feldner (1988)	2	19	90.5%	16-58
Resch, Stenstrom, Egund (1989)	3	22	88.0%	20-69
Mauldin, Sanders, Whitmer (1990)	1	29	96.7%	26-74
O'Doherty, Lowrie, Magnussen (1990)	11	70	86.4%	>45
Conlan, Gregg (1991)	0	29	100%	49-79
Vallier, Peterson, LaGrone (1991)	16	44	73.3%	46-80
Mann, Rudicel, Graves (1992)	8	67	89.3%	10-83
Total	117	1392	92.2%	

Several studies that are not subject to the sample bias previously discussed have been carried out using sample populations not drawn from surgical programmes. Merrill et al. (1967) in a study of 1,011 nursing home patients report hallux valgus in 30% of females as oppose to 7% in males. They stated: "*The difference in incidence of hallux valgus between sexes is not surprising since we find, in general practice, that more women than men have hallux valgus.*" However, they did not attempt to interpret this discrepancy. Marr and D'Abrera (1985), in their survey of foot problems among 191 school children reported a prevalence of 11.8% in females as oppose to only 3.5% in males. The Wessex Foot Health Survey (Brodie et al. 1988) compared the prevalence of hallux valgus at different age groups with data concerning suitability of footwear. They contended that the assumption that hallux valgus is a genetic or biomechanical problem and not due to footwear was questionable and concluded: "*Unless it can be shown that females are more likely to have this genetic trait than males, that assertation could be open to question.*"

Kilmartin and Wallace (1994) reported a prevalence of hallux valgus in the order of 2.3% in 6,000 nine-year-old school children. Of these 122 children, 16 were male and 106 were female. The authors did not attempt interpretation of this preponderance of females. Clearly, hallux valgus affects both sexes; however, the condition appears more prevalent in females. Uncertainty exists as to the underlying reason for this. Many authors have assumed that this is due to an abnormality present on the X chromosome. Thus, a brief discussion on sex-linked traits appears justified here.

When only one gene and, thus, only its locus on one chromosome of a pair needs to be abnormal for a condition to be expressed, it is said to be a dominant condition. When, in order for a condition to be expressed, both genes at the same loci on a pair of chromosomes must be abnormal, it is recessive. If the abnormal gene is on the X-chromosome, the condition is X- linked or sex-linked. X-linked dominant inheritance is seen in successive generations. An affected female parent would produce one half of her male offspring and one half of her female offspring affected. An affected male parent would produce all affected female offspring since they would receive an X-chromosome from their father; such a male parent would produce all normal male offspring since they would receive a Y-chromosome from the father.

Carrier mothers, who are clinically normal having normal or affected sons characterise X-linked recessive conditions. Carrier mothers have normal or carrier daughters. A male offspring who receives the abnormal X from the mother would be affected since he has only one X-chromosome. Conversely, if he received the normal X from the mother, he would be normal. Female offspring who receive a normal X from their mother would be normal and not carriers. If a female offspring received the affected X from her mother, she also has a normal X from her father, and since only one X is abnormal, she will be a clinically normal carrier. When an affected male produces offspring all his sons are normal and all of his daughters are carriers. Thus, in view of the preponderance of affected females, it would appear that if hallux valgus is X-linked, it displays the characteristics of a X-linked dominant trait. Clearly, this contrasts with the results of Johnston (1956), who concluded that the condition displayed the characteristics of an autosomal dominant trait, where every affected individual should have at least one affected parent (exceptions may occur if the gene in question has a high mutation rate) and both males and females should be affected with equal frequency.

A further explanation for the increased prevalence of hallux valgus observed among females may lie in the increased prevalence of ligamentous laxity observed in this gender. Young females have a propensity for ligamentous laxity (hypermobility) (Schuster and Port 1977, Bird 1983, Scranton 1983, Thomson 1993). Hypermobility is strongly influenced by the female hormones: progesterone, oestrogen and relaxin (Schuster and Port 1977, Thomson 1993). Relaxin is predominantly produced by the corpus luteum and is necessary for "relaxing" the normally taut ligamentous structures around the pelvis to aid in birth. Schuster and Port (1977) maintained that this hormone could be passed to the fetus where its effects may result in persistent generalized ligamentous laxity and that females are more susceptible to these effects than males. They further suggest that hormonal ligamentous laxity is inherited, but provide no empirical data to support this theory.

Several authors have cited ligamentous laxity as an associated / causative factor in hallux valgus (Grode and McCarthy 1980, Marr and D'Abrera 1985, Pressman 1987, Kalen and Brecher 1988, Carl et al. 1988, Bouysset 1991) and also in pes planus (Kolker 1973, Page 1983, Pressman 1987, Kalen and Brecher 1988, Hamill et al. 1989, Rao and Joseph 1992, Welton 1992), but few provide data to support their contentions.

Carl et al. (1988) reported a statistically significant correlation between hallux valgus and generalized hypermobility in a controlled trial (20 patients, 20 controls) ($P<0.01$). They contended that genetically predisposed lax ligamentous structures and loose joints of the foot, particularly at the 1st MPJ and metatarsal cuneiform joints, may be traumatised by environmental stimuli such as footwear and moreover, that this may result in hallux valgus. Furthermore, they suggested that trauma or overuse of the joints may lead to further hypermobility. Clearly, the wearing of shoes too tight or narrow may result in both trauma and overuse, particularly among females, adding to both the hypermobility and the deformity.

2.4.2.3 Footwear As a Cause of Hallux Valgus

"Bunions with symptoms can develop in feet with no pathodynamic anomaly. In such instances one can say that shoes caused the bunion to develop." (Rothbart 1972)

Ill-fitting footwear was perhaps the first factor considered as an aetiological factor in hallux valgus (Clough and Marshall 1985). Indeed, Durlacher (1845) noted: "*One of the most certain causes of a bunion is the wearing of shoes made too short and with a narrow sole.*" Clearly, the design of shoes has changed dramatically since this time. However, the prevalence of hallux valgus remains unacceptably high within the population. Are shoe manufacturers still being forced to produce unsuitable footwear due to the demands of fashion? Does the encasement of the foot in any form of covering, irrespective of shape and design result in the onset of hallux valgus? Alternatively, the argument remains that footwear plays no role in the development of the deformity. Several studies have attempted to identify the relationship between shoe wearing and hallux valgus and, more recently, the specific role of shoes in the development of the deformity.

Hoffman (1905) noted that, when barefooted, the toes separated on weightbearing, with each phalanx in line with its metatarsal, whereas shoe wearing crowded the toes and caused abduction of the forefoot. James (1939) advanced a similar proposal. Studying 65 barefoot Solomon islanders, he reported that the forefoot adducted on the rearfoot, with each digit in line with its metatarsal. Conversely, in shod Europeans the forefoot abducted on the rearfoot by approximately 20°. He postulated that this increased first ray loading, which may lead to the development of hallux valgus.

Barnicott and Hardy (1955) used footprinting to measure the angle of 1st MPJ abduction in a barefooted Nigerian population. Comparisons were made with results obtained from age-matched Nigerian soldiers who wore army issue boots and a group of European university students and nurses of mixed gender with clinically normal feet. They reported a statistically significant difference between the Nigerian females and European females, but no significant difference between the shod and unshod Nigerians (males and females).

The greater deviation of the hallux observed in the European females when compared to the European males was believed to be due to constrictive female footwear. The smaller difference between genders in the Nigerian population supported this conclusion. However, no details of the type of shoes worn by the females, or the length of time for which the army boots had been worn was provided. Since little difference existed in the results obtained from the shod and unshod Nigerian populations, racial factors may have been significant. No test of the methodologies repeatability was presented.

Sim-Fook and Hodgson (1958) concluded that the wearing of shoes led to the development of hallux valgus following their comparative study of 107 barefooted Chinese and 118 Chinese who wore either canvas slip on shoes or wooden soled sandals. Results of clinical and radiological examinations revealed a 33% prevalence of hallux valgus among the shod and a prevalence of only 2% among the unshod. Interestingly, metatarsus primus varus, a component of the hallux valgus deformity, and a suspected aetiological factor in hallux valgus, was present in only 6% of the shod, as compared to 24% of the unshod. However, since no diagnostic criteria were presented for these deformities, the results of this study must be considered with caution.

Kilmartin and Wallace (1993) argued that the populations studied by Fook and Hodgson (1958) were poorly matched: the unshod population were selected from a fishing community, who used their feet to hold fishing lines taut, leaving their hands free to work. Clinical examination of this population revealed a "*remarkable degree of prehensile strength*" within the hallux. Kilmartin and Wallace (1993) postulated that this may be considered as a form of exercise therapy that could prevent the deformity. Indeed, Groiso (1992) demonstrated the beneficial effects of exercise therapy in the treatment of hallux valgus.

Shine (1965) studied the islanders of St. Helena of whom 1,400 went barefoot, and 1,606 wore shoes. A linear relationship between the prevalence of hallux valgus and the length of time for which shoes had been worn was reported. However, the effect of increasing age on the condition may have obscured these results if this effect is separate from the effect of long term shoe wearing. The shod populations were all grouped together. Some subjects had been using shoes for more than 60 years while others had only been shod for one year. The authors present a diagnostic criterion for the condition. However, they did not test the assessment techniques' repeatability or validity..

Maclennan (1966) studied 1,256 barefooted subjects in New Guinea (665 males, 591 females). The author reports a prevalence of hallux valgus of the order of 1% in males and 4% in females. Clearly, this prevalence is lower than has commonly been reported for shod populations. However, shoes could have played no role in the development of the deformity within this population and cannot, therefore, explain the gender differences in the prevalence of hallux valgus within this population.

Meyer (1979) compared the foot skeletons of 50 unshod Pecos Indians with 50 medieval Yugoslavian peasants who had worn some type of leather footwear. Unshod and shod populations displayed mean 1st MPJ angles of 6.5° and 14° respectively. The accuracy of measurements made from skeletons is questionable. The relationship between the hallux and its metatarsal is dependent on the supporting soft tissue structures that encompass the 1st MPJ. The decomposition of these structures, which must have occurred, would clearly have influenced the observed bony relationships. Moreover, no influences of racial or social factors were considered. Furthermore, the small sample group cannot be considered as representative and so the general conclusions that can be drawn from this study are limited. However,

even in the shod population, the mean 1st MPJ angle was only 14°. This falls just within the commonly set criteria for normality.

Gottshalk et al. (1981) reported that hallux valgus occurred among both urban and rural, black, South African women, but with less frequency than in white women. All subjects were over fifty years old and shod. There was a significant difference between black and white groups ($p=<0.01$), but not between the two black groups. They concluded that hallux valgus was due, not to wearing of shoes, but to some basic abnormality of the foot. Noakes (1981) supported this view.

In a Gallup Organisation survey (1986) 59% of women said they wore high heel shoes from 1-8 hours per day (Gastwirth et al 1991). Sussman and D'Amico (1984) measured the heel height of 200 shoes and noted that on average the heel height of female shoes was 2.5 times higher than that in male shoes. Several authors have employed force plate analysis in combination with X-rays to evaluate the effects heel height has on foot function and gait.

Schwartz and Heath (1959) made a preliminary study of the osteo-articular changes within the foot found in association with increasing heel elevation with and without shoes and also differences in shank curvature found in shoes of different heel heights. Measurements were made from a series of 65 lateral X-rays made of 2 females. The authors concluded that the measurements *"strongly suggest"*:

1. The length of the foot distal to the first metatarsal head does not change significantly as heel height is increased.
2. The heel to ball length of the barefoot may shorten slightly when the heel is raised passively or actively.
3. Shortening of the heel to ball length of the foot when shoes are worn is double that observed in barefoot.
4. This shortening occurs in association with elevation of the longitudinal arch of the foot by shoe shank, accompanied by a hinging of the foot at the cuneonavicular and talonavicular joints.

The observation of shortening of the foot, in association with elevation of the medial longitudinal arch, suggests that the foot is supinated in high-heeled shoes. However, the observation of hinging of the foot at the cuneonavicular and talonavicular joints suggests that the midtarsal complex is unlocked; a feature commonly associated with the pronated foot. Thus, the results of Schwartz and Heath (1959) appear

confused, providing evidence of both increased supination and increased pronation in association with increasing heel height. Clearly, these conclusions must be considered with caution as measurements were made on only 2 female subjects.

The consequences of high-heeled shoes on the 1st MPJ reaction forces during the gait cycle were investigated by McBride et al. (1991). A summary of their results follows:

1. Wearing high-heeled shoes significantly alters the loading pattern of the 1st MPJ during the push off phase of gait.
2. Wearing high-heeled shoes caused the forces at the 1st MPJ to be twice the magnitude of the forces obtained in the same subjects during barefoot walking.
3. The joint reaction force between the metatarsal head and the sesamoid bones showed values of 0.44 and 1.03 times body weight while in bare feet and high-heels, respectively.

The results of McBride et al. (1991) suggest that the wearing of high-heeled shoes transfers the course of ground reaction forces closer to the first metatarsal. This allows more of the total force to act directly on this bone. It should be noted that many styles of high-heeled shoe have a relatively narrow forefoot width that will force the toes together, allowing a smaller lateral base of support and a smaller area for the course of the ground reaction force to traverse. These results concurred with the observations of Schwartz et al. (1964) who noted a decrease in weightbearing of the fifth metatarsal head which was correlated with increased loading of the medial forefoot and increased pronation.

McBride et al. (1991) concluded that an increase in the ratio of forces accounted for approximately 78% of differences between high-heeled and barefooted gait. Since velocity of gait was unaltered, this variable had no influence. Change in the kinematics at the joint may account for the remaining 22% of differences. At peak resultant joint force, the angle of the first metatarsal to the horizontal was increased by approximately 8° in high-heeled gait. Furthermore, the authors reported a superior shift of approximately 4° in the angle of the resultant joint force about the anterior shaft of the metatarsal. These kinematic changes may have effects on the articulation between the metatarsal head and the sesamoids. In the dorsal direction, the crista separating the two sesamoids becomes less prominent. Thus, it provides a more shallow depression for sesamoidal articulation. Increased inclination of the metatarsal while walking in high heels will force sesamoidal articulation in these more shallow regions.

This may increase the potential for sesamoidal subluxation, particularly as the first ray plantarflexes during propulsion and further increases the inclination of the first metatarsal, forcing the sesamoids to articulate even more distally on the metatarsal head.

The theories of McBride et al. (1991) help to substantiate the association between high-heeled shoes and instability of the 1st MPJ. However, since a study population of only eleven females was reported, and results are dependant upon the validity of the biomechanical model presented, the results of these workers must be interpreted with some caution.

A slightly larger sample was employed by Gastwirth et al. (1991) in their study of foot function in shoes of varying heel heights. 43 female subjects underwent electrodynographic gait analysis in barefoot, low-heel shoe and high-heel shoe conditions. Comparisons of segmental foot function, actual pressures and pressure duration's were determined. Gastwirth et al. (1991) found no evidence of abnormal pronation in high-heels and noted that this was contrary to the results of earlier workers (Schwartz et al. 1964, Soames and Evans 1987). The authors maintained that an increase in the duration of forefoot loading, rather than an increase in actual pressure, was responsible for pedal pathology. Thus, Gastwirth et al. (1991) propose that it is the impulse of the force that is significant, since:

force x time = impulse

Gastwirth et al. (1991) theorise on the pathomechanical consequences of wearing high-heels. They contend that high-heels accelerate the formation of hallux valgus by the following mechanism: the shape of high-heel shoes will dorsiflex and laterally deviate the hallux on its metatarsal head. The results of the study showed a significantly longer hallux loading in combination with a nonsignificant increase in actual pressure beneath the hallux in high-heels. Gastwirth et al. (1991) maintained that this would create a force pushing the first metatarsal head medially, causing the sesamoid apparatus to track laterally and distally because of its insertion into the base of the proximal phalanx of the hallux. They believed that this would cause erosion of the intersesamoidal cristae. Gastwirth et al. (1991) believed that hallux valgus may ensue via this mechanism even when the first ray is not hypermobile. Furthermore, they contend that the stability of the first ray may be increased in high-heels, since the

foot is supinated. This supinated position, they believed, would allow peroneus longus to maintain its plantar vector pull on the first ray and the dorsiflexed hallux would reduce hypermobility by pushing the metatarsal head plantarly. Further research is required to detect the accuracy of this hypothesis, since the observation of increased supination in association with high heels is, as the authors' point out, in marked contrast to the reports of other workers who have observed an increase in pronation in high-heel gait.

Phillips et al. (1991) studied the effects of high-heels on subtalar joint motion in five females (age 22-40). High speed video analysis was used to examine rearfoot motion during gait. The authors' findings suggest that the wearing of high-heels creates rearfoot instability predisposing the foot to either abnormal pronation or supination, depending on the position of the forces acting on the foot and the position of the subtalar joint axis. Moreover, minimum inversion and eversion of the foot occurs when the ground reaction force is centred directly under the subtalar joint axis. By moving the position of the heel medially and laterally, Phillips et al. (1991) demonstrated that the degree of rearfoot stability could be increased or decreased by the heel positioning. It was noted that the greatest pronation of the foot occurred when the heel counter was positioned 2mm lateral to the centre of the shoe and that maximal stability was obtained with the heel counter positioned 2-4 mm medial to the centre of the shoe. Again, the small sample size diminishes the representativeness of the observations made.

Rao and Joseph (1992) compared arch height indices (AHI) in children who habitually wore shoes and children who had never worn footwear (1555 shod, 745 unshod). Static footprints were obtained using inked rubber mats. 154 children (6.7%) were diagnosed as flat footed. A significantly higher prevalence of pes planus existed in children who wore shoes (8.6%) than among the unshod (2.8%) ($P<0.001$). This result supports the contentions of Didia and Nyenwe (1988) who believed that shoewearing influenced the development of the medial longitudinal arch. Interestingly, Rao and Joseph (1992) also reported that 710 children displayed ligamentous laxity. The ratio of flat foot in children with ligamentous laxity was 14.4% compared with 3.35% in those who had no ligamentous laxity. The preponderance of flat foot also varied with the type of footwear worn. Rao and Joseph (1992) concluded that shoes which encased the toes were more detrimental to arch development than open-toed sandals or slippers and that

the detrimental effects of closed-toe shoes were enhanced in the presence of ligamentous laxity. Clearly, the female propensity for ligamentous laxity may lead to an increased preponderance of pes planus in this gender. If pes planus and/or ligamentous laxity are associated with hallux valgus, this may provide an explanation for the increased prevalence of hallux valgus observed among females.

Observations that the tighter, more pointed shoes of females, were associated with a higher prevalence of hallux valgus were the basis of the theory of footwear as an aetiological factor. However, these earlier observations were largely intuitive with little or no basis of understanding of the intrinsic structure of the foot, the mechanism of foot function, or the causative process by which the deformity manifests (Clough and Marshall 1985). Despite this lack of understanding, it does appear fair to assume that a poorly designed and ill-fitting shoe has a greater potential to exert a detrimental effect on the foot than one which is anatomically designed and well fitting.

In the light of more recent work (Gastwirth et al. 1991, McBride et al. 1991, Phillips et al. 1991), there is stronger evidence to suggest that footwear may play an excitatory role in the development of hallux valgus. However, the small samples used in these studies diminishes their representativeness relative to the wider population. From the results of these investigations, it is evident that two distinct theories regarding the effects that high-heel shoes have on foot function exist. The results of McBride et al. (1991) support the theory that the wearing of high-heels results in an increase in foot pronation. However, the results of Gastwirth et al. (1991) appear to provide evidence in support of a theory of increased supination in association with high heels. It is uncertain which of these theories is correct.

The observations of Phillips et al. (1991) suggest that the effect high-heels have on foot function may be dependent upon the design of the shoe being worn, specifically the positioning of the heel. Moreover, that the position of the wearer's subtalar joint axis may be the determining factor of whether the foot becomes pronated or supinated when wearing high-heels. If the moment of the ground reaction force exerted through the heel of the shoes (during gait / static stance) onto the plantar foot, lateral to the subtalar joint axis is greater than the moment of the force exerted medial to subtalar joint axis, it will have a pronatory effect. This should also unlock the midtarsal joint and render the first ray hypermobile. However, if the medial moment is greater than the lateral moment, it will have a

supinatory effect; locking the midtarsal joint and making the first ray more rigid. Given that positional variation in the subtalar joint axis exists within the population (Isman and Inman 1969), it is possible that identical shoes may cause foot pronation in one individual and supination in another, or even pronation of one foot and supination of the other, in the same individual.

Theories of hallux valgus development in association with both increased pronation (Root et al. 1977) and increased supination (Gastwirth et al. 1991) have been proposed. Both mechanisms are contentious and untested. Furthermore, it is possible to present a further hypothetical mechanism in which both supination and pronation have a role.

If high-heels do increase foot supination during wear as Gastwirth et al. (1991) suggest, and are worn for prolonged periods, over time accommodative shortening of the calf muscles may occur. Passive stretch of these muscles during joint flexion-extension is an important factor in the maintenance of the normal physiologic length. Reduction of the stretch stimulus may lead to accommodative shortening of the muscles. The wearing of shoes with a heel pitch reduces tension in the calf muscles and may produce an accommodative shortening of the muscles. This may reduce the range of dorsiflexion available at the ankle joint (Rome 1988).

Restoration of the stretch stimulus by a decrease in heel-height will only result in a return to the original muscle length if the muscle has not fibrosed in a shortened state. Rome (1988), states that *"It is important to remember that with younger adults wearing fashionable footwear the likelihood of fibrosis occurring increases twofold, and that for a prolonged period of time the muscle may fibrose, and restoration of the stretch will not result in restoration of physiological length."* If an individual exhibiting fibrosis due to the prolonged wearing of high-heels, where to wear lower-heeled shoes for any period, compensatory subtalar and midtarsal joint pronation may be required in order to allow 10° of dorsiflexion at the ankle before heel lift during gait (Root et al.1977), or simply just to bring the heel into contact with the ground. This may result in first ray hypermobility and possibly hallux valgus if the theories of Root et al. (1977) are correct. Thus, it may be the transition to the use of low-heeled footwear (perhaps due to a change in fashion trends) after prolonged use of high-heeled footwear that

initiates the sequence of events that result in hallux valgus. Further research is required to detect the accuracy of this theory.

Hallux valgus is more common among shoe wearing populations than among the unshod. Many of the mechanisms proposed for the development of hallux valgus, in association with shoe wearing, although untested, appear theoretically plausible. However, a prevalence of the deformity exists within barefooted populations, suggesting that external force induced by footwear, acting on the foot, should not be considered (in isolation) as the sole cause of hallux valgus.

2.4.2.4 Abnormal Pronation As a Cause of Hallux Valgus

"We regard the majority of cases of hallux valgus as acquired deformities resulting from pronation of the foot. The role of footwear is secondary, serving to aggravate in mild deformity or produce manifest deformity where only potential hallux valgus previously existed as a result of foot pronation." (Jordon and Brodsky 1951)

The association between hallux valgus and foot pronation has been noted for over a century (Riedel 1886, Goldthwait 1893). However, little empirical evidence exists to prove that hallux valgus is more common in subjects with abnormally pronated feet. Hoffman (1905) noted that a pronated foot is always associated with, and is always the cause of, hallux valgus. These overstated contentions were not supported scientifically. Conversely, Kelikian (1965) suggested that prevalence of pes planus in isolation was far greater than the prevalence of pes planus and hallux valgus in combination. However, Kelikian (1965) did hypothesise upon a possible mechanism of the actiology of hallux valgus in pronated feet. He contended that the collapse of the medial longitudinal arch depressed the base of the first metatarsal plantarly, while the first metatarsal head was elevated. It was assumed that the medial capsule of the 1st MPJ was structurally weaker than the lateral aspect. Thus, the capsule offered less resistance than the base of the proximal phalanx. Consequently, the metatarsal subluxated medially.

Root et al. (1977) advanced a different actiological mechanism. They proposed that abnormal subtalar joint pronation caused pes planus. Abnormal subtalar joint motion was assumed to unlock the midtarsal joint, which, they contended, rendered the forefoot hypermobile. The hypermobile first metatarsal head then inverted in relationship to the hallux and subsequent subluxation of the 1st MPJ followed.

It was assumed that the axially rotated position of the first metatarsal was significant in the lateral displacement of the sesamoid apparatus. Root et al. (1977) hypothesised that articulation between the tibial sesamoid and the intersesamoidal crista resulted from the position of the first ray. Consequential erosion of the crista further reduced the normal anatomy and function of the first ray. A force vector, directed through the hallux to the 1st MPJ, was assumed to be caused by contact between the hallux and its neighbouring toe. Further varus deviation of the first metatarsal and deterioration of the condition resulting from this was proposed. However, Sanders et al. (1992) suggest that splaying of the first metatarsal occurs in hallux valgus whether the hallux is in contact with the second toe or not.

The primary detraction from the theories of Root et al. (1977) is the lack of clinical research carried out by these workers to substantiate their contentions.

Inman (1974), D'Amico and Schuster (1979) and Oldenbrook and Smith (1979) disputed the theory of first ray motion proposed by Root et al. (1977) They suggested that the hypermobile first ray everted when dorsiflexed, and assumed that the hallux underwent the same motion.

Greenberg (1979) concluded that there was more pronation than normal in hallux valgus following his radiographic investigation of the association between the conditions. However, certain methodological weaknesses exist in this study: 312 dorsoplantar X-rays were taken of subjects awaiting hallux valgus surgery. The radiographs were divided into severe and mild hallux valgus. 1st MPJ angles were measured to make this distinction (Severe = >28°, Mild = <11°). However, Piggott (1960) suggested that an angle <11° could not be considered abnormal. Greenberg (1979) measured the following radiographic angles: calcaneal inclination angle, talar declination angle, lateral talo-calcaneal angle, dorsoplantar talo-calcaneal angle, cuboid abduction angle and talo-cuboid angle. Kilmartin and

Wallace (1993) acknowledged the frequent use of the first four of these angles as an index of subtalar joint pronation, but expressed concern regarding the validity of the latter two angles.

Greenberg (1979) made comparisons between his own results and normal values obtained by another worker. No statistically significant difference was found between the normal and hallux valgus results except the cuboid abduction angle and the talocuboid angle. These two angles being unique to the study, it is difficult to imagine how Greenberg (1979) could have made comparisons for these angles. Moreover, unless interobserver repeatability and validity are tested, comparisons of this nature are clearly unacceptable. Greenberg (1979) reported no tests of this nature.

Sixty-three of the severely pronated feet were selected from the original sample. High talar declination and talo-calcaneal angles were applied as measures of subtalar joint pronation. No significant difference in the prevalence of mild or severe hallux valgus was found between this subgroup and the main study group. Thus, the link between the amount of abnormal pronation and hallux valgus is unclear. How much abnormal pronation must occur before hallux valgus develops? Phillips and Lidtke (1992), demonstrated that this is likely to vary between individuals, dependant upon the axial positions of both the subtalar and the midtarsal joints.

Kalen and Brecher (1988) also used radiological techniques in an attempt to identify the relationship between juvenile hallux valgus and pes planus in a series of 66 adolescents (mean age= 13 years). 56% of these subjects presented with abnormally low, calcaneal inclination angles and high, dorsoplantar, talo-navicular angles. It is unclear what was considered as low or high since no control values were established. No correlation between hallux valgus and any of the radiological measures was reported. It is clear, however, that 40% of the study group exhibited hallux valgus without pes planus.

Kilmartin and Wallace (1992) used footprinting techniques in their study of the significance of pes planus in juvenile hallux valgus. Their study population consisted of 96 eleven-year-old school children of mixed gender (32 with bilateral hallux valgus, 64 with no abnormality of the 1st MPJ). No statistically significant difference was found between the arch indexes of the two groups. They

concluded that height of the arch had little importance in juvenile hallux valgus and that the role of pes planus in hallux valgus was questionable.

These observations are in part supported by the results of Staheli et al (1987) who demonstrated that pes planus was usual in infants, common in children and present within adults, following their footprinting study of 441 otherwise normal individuals.

Kilmartin, Barrington and Wallace (1994) also indirectly tested the relationship between abnormal subtalar joint pronation and hallux valgus, in a controlled trial of the effectiveness of foot orthoses in the treatment of juvenile hallux valgus. This study tested the effect of reducing abnormal subtalar joint pronation, using orthoses, on the development of hallux valgus. Their study population consisted of 122 children (between the age of nine and 10 years) who exhibited either unilateral or bilateral hallux valgus. The children were randomly assigned to receive either no treatment or foot orthoses. The 1st MPJ angles were measured again in 93 of the subjects, approximately three years later. 1st MPJ angles were found to have increased in both the study and control groups, but more markedly in the study group. Hallux valgus was also noted to have developed in the previously unaffected feet of the children with unilateral hallux valgus, despite the use of orthoses. Thus, based on this study it appears that abnormal pronation may have little part in the development of hallux valgus. However, it is possible that the orthoses used in this study did not sufficiently prevent abnormal pronation from occurring during the gait cycle. Interestingly, an attempt to standardise footwear was abandoned because of poor compliance by the children. No measure of compliance for the orthoses was reported.

Schuster and Port (1977) considered the female hormones, progesterone, oestrogen and relaxin to play a significant role in the aetiology of abnormal pronation by relaxation of ligamentous structures. Indeed, as previously stated, several authors contend that pes planus is commonly associated with ligamentous laxity (Kolker 1973, Page 1983, Pressman 1987, Kalen and Brecher 1988, Hamill et al. 1989, Rao and Joseph 1992, Welton 1992). Of these, Rao and Joseph (1992) are the only ones that provide data to substantiate this conjecture. However, if abnormal pronation and is an actiological factor in hallux valgus, the increased potential for the female foot to be abnormally pronated, due to the greater

preponderance of females exhibiting ligamentous laxity, may account for the higher prevalence of hallux valgus observed in females.

The evidence presented neither confirms, nor dispels the existence of a relationship between hallux valgus and pronation. Moreover, it highlights the problem encountered repeatedly throughout this review, that of differentiation between cause and effect. Root et al. (1977) proposed that hypermobility of the forefoot during the gait cycle resulted from abnormal rearfoot pronation. This, in combination with the lengthening of the foot associated with pronation, may greatly increase the deforming effects of constrictive footwear. However, the relative length of the metatarsals and the digits may also be of significance. Is a foot likely to be mechanically disadvantaged, and more exposed to deforming forces in the presence of a relatively longer first metatarsal or hallux? The following section reviews the literature concerning the role of metatarsal length and position in hallux valgus.

2.4.2.5 Relative Metatarsal Position

"The longer the metatarsal, the greater the excursion at its head. This increased motion increases the instability of the metatarsophalangeal joint and also the chances for abnormal movement" (Janis and Donick 1975).

It has been suggested that differences in relative metatarsal length patterns are characteristic of different races (Hawes et al. 1994). This observation is largely intuitive, being made from the differences in the portrayal of digital and metatarsal protrusion in ancient art (Klaue et al. 1994). Craigmile (1953) and, later, McCarthy and Gessner (1993) maintained that relative metatarsal length patterning is genetically determined at the time of fertilisation and remains constant throughout life. Morton (1930) believed that a short first metatarsal was congenital and contended that short or hypermobile first rays were dysfunctional and would pronate the foot and, thus, lead to deformity. Morton also maintained that when weightbearing stresses become concentrated upon the second metatarsal as a result of first ray dysfunction, enlargement and lengthening of the second metatarsal

occurred in response to the increased force acting upon it, increasing the length differential between the first and second metatarsals. Stott et al. (1973) supported this conjecture.

Wolff's law (1884) states that "Every change in the use or static function of bone causes a change in its internal form and architecture as well as alterations in its external formation and function, according to mathematical laws" (Brahm 1988). If second metatarsal lengthening does occur as Morton (1930) maintained, it seems likely to be in accordance with Wolff's law.

Shereff et al. (1990) reported that on lowering of the medial longitudinal arch, the first metatarsal was significantly lengthened (relative to the lesser metatarsals), following their extensive study of weightbearing and non-weightbearing radiographs. Lord et al. (1992) supported this view, suggesting that, on weight-bearing, flattening of the medial longitudinal arch results in an anterior motion of the metatarsal heads as the midfoot lowers.

Nilsonne (1930) compared relative metatarsal lengths in hallux valgus and normal subjects. The study population consisted of 618 subjects of whom 121 exhibited hallux valgus and 497 clinically normal feet. 5.8% of the hallux valgus group displayed relative protrusion of the second metatarsal, a further 5.8% had equal length first and second metatarsals and 88.4% displayed a longer first metatarsal. The prevalence of relative first metatarsal protrusion in association with hallux valgus was significant in comparison to the normal group, who exhibited a longer second metatarsal in 52.2%, an equal length differential in 13.4% and longer first metatarsals in 34.4%. Nilsonne presented no criteria for diagnosis of hallux valgus and no results of a repeatability study.

Harris and Beath (1947) found no data in their investigation to support Morton's contentions in their study of 7,167 feet. However, the methodologies used were significantly different. Relative protrusion of the first metatarsal was identified in 2,693 feet. Relative protrusion of the second metatarsal was identified in 2,878 feet and 1,596 feet displayed equality between first and second metatarsals. They found no association with pathology.

Hardy and Clapham (1951) identified a weak association between relative metatarsal protrusion and hallux valgus. Their study population incorporated 91 subjects with hallux valgus and 84 control

subjects. The first metatarsal was on average 4mm longer than the second metatarsal in the hallux valgus group; in the control group the first metatarsal was repeatedly longer than the second metatarsal, but only by an average of 2mm. Despite an evidently small arithmetical difference, a highly significant statistical difference was exhibited between the hallux valgus group and the control. A weak correlation ($r= 0.16$, $r^2=0.03$) was found between relative protrusion of the first metatarsal and hallux valgus.

Plaster (1954) also proposed that hallux valgus was closely related to the length of the first metatarsal. He stated: *"More research should be done regarding the first metatarsal length pattern as a whole. Such consideration will make for, at least, a more scientific approach to the multitude of structural variances found in the forefoot."*

Conversely, Du Vries (1973) argued that relative metatarsal length had no direct importance in hallux valgus and that it is common to see hallux valgus with both long and short first metatarsals. He concluded that the relationship between metatarsal length pattern and hallux valgus was "*fortuitous*".

Inman (1974) concurred with Du Vries' contentions. Upon consideration of the proposal that an excessively long first metatarsal may anatomically predispose to hallux valgus, he concluded that this theory was based upon "*minimal anthropometric data and unsubstantiated by mathematical analysis.*"

More recently, Heden and Sorto (1981) measured relative metatarsal protrusion and hallux length in their comparative study. Comparison was made between 200 dorso-plantar radiographs of patients admitted for corrective hallux valgus surgery and 100 dorso-plantar radiographs of patients admitted for surgical correction of foot pathologies other than hallux valgus, in an attempt to identify a relationship to hallux valgus. The distance from the distal metatarsal articulating surface to the end of the digit, including the soft tissue outline, defined hallux length. The authors' justification for including the soft tissue outline was that it was felt that shoe pressure exerted a lateral force here and not directly on the bone. Results showed a mean relative first metatarsal protrusion of 1.03mm in the hallux valgus group and a mean relative second metatarsal protrusion of 1.77mm in the comparative group.

Duke et al. (1982) used 93 anteroposterior x-rays of the foot in their study of relative metatarsal lengths. Statistical analysis revealed a probability >99% that subluxed 1st MPJ's had at least 1mm of first metatarsal protrusion. Furthermore, there was a 99.5% probability that congruous 1st MPJ's would have <1mm of first metatarsal protrusion. Moreover, Congruous joints averaged 1.7 mm of second metatarsal protrusion. Two-thirds of the congruous joints displayed second metatarsal protrusion. The remaining one third had an average of 0.73 mm of first metatarsal protrusion.

Saragas and Becker (1995) used a controlled trial of 52 hallux valgus feet and 66 feet without the deformity in their study of relative metatarsal length patterns in hallux valgus. Although the authors report a significant statistical difference in the first to second metatarsal length ratios of the two groups (P=0.003), they conclude that, clinically, this difference (82% Vs 84%) is negligible and that metatarsal length plays no role in the hallux valgus deformity.

Turgut et al. (1997) examined the digital patterning among 150 female and 155 male Turkish students (age 17-25). In male students the prevalence of a long second toe was 9.03% in right feet and 11.03% in left feet. The prevalence of having equal length second and first toes was 5.8% in right feet and 3.24 in left feet. Among the females the prevalence of a long second toe was 6.66% in right feet and 8% in left feet. The prevalence of having equal length second and first toes was 4.66% in right feet and 2% in left feet. A statistically significant difference was identified between male and female average values of right and left second toes length (P<0.01). No statistically significant difference was observed in the ratios of males and females having equal first and second toes in right and left feet (P>0.05) or in the difference between the ratios of male and females having longer first toes than the second toes (P>0.05).

If a length differential between the first and second digits is an actiological factor in hallux valgus, the observations of Turgut et al. (1997) suggest that the increased prevalence of hallux valgus observed among females is unlikely to be accounted for by gender differences in digital patterning alone since no statistical differences were observed between genders. However, Turgut et al. (1997) made no reference to whether the subjects were biomechanically normal or not, or to the presence of any foot pathologies

within the sample. If the contentions of Morton (1930), Sherreff et al. (1990) and Lord et al. (1992) are correct this may have had an influence on the results obtained.

There are many inconsistencies in the literature concerning metatarsal and digital length patterns. These are largely due to a lack of standardisation of methods. From a purely mechanical view however, it seems likely that a longer first metatarsal, could provide augmentation of movement at the metatarsal head, which may lead to instability of the 1st MPJ and therefore, an increased probability of abnormal function at this joint. Moreover, protrusion of the first metatarsal and / or a long hallux may predispose this digit to be subject to valgus forces from footwear.

In addition to variation in relative lengths of the metatarsals, variation in the neutral position of the first metatarsal in the sagittal plane exists within the population. Is this sagittal plane position of the metatarsal significant in the development of hallux valgus?

Hardy and Clapham (1951) subjectively assessed the mobility of the first metatarsal at the first tarsometatarsal joint. They classified the results into three groups: free mobility, limited mobility and no mobility. In subjects showing a 1st MPJ angle ≥15°, 63% exhibited free mobility, 18% displayed limited mobility and 19% had no mobility. The subjectivity of these findings diminishes their value.

The importance of a flexible plantar flexed first ray was highlighted by Kilmartin, Wallace and Hill (1991) in their comparative study of 140 clinically normal feet and 140 juvenile hallux valgus feet. They noted that 65% of the hallux valgus group exhibited a plantarflexed first metatarsal in excess of 2mm. It was concluded that "*no other single abnormality of the lower limb position or function is so strongly associated with the hallux valgus foot.*" This conclusion appears overstated. Furthermore, the method adopted by the authors to calculate the relative position of the first metatarsal excluded a zero position. The implications of this omission on the authors results are not entirely clear.

If a plantarflexed first metatarsal is an important predisposing factor in hallux valgus, it is essential to understand the theory of pathomechanics responsible for the development of hallux valgus in relation to the plantarflexed metatarsal position. Two distinct concepts exist. Root et al. (1977) suggested that ground reaction forces push the hypermobile first ray into a dorsiflexed and inverted position. This

results in a torque developing at the 1st MPJ as the plantarflexors of the hallux attempt to stabilise this joint during propulsion. Motion at the normal 1st MPJ occurs in the sagittal and transverse planes. The frontal plane motion (inversion) occurring in the first metatarsal leads to subluxation between the hallux and its metatarsal. Hicks (1953, 1954), Ebisui (1968) and later, Kelso et al. (1982) supported this theory.

Inman (1974), D'Amico and Schuster (1979), Oldenbrook and Smith (1979) and Wanivenhaus and Pretterklieber (1989) disputed this theory. They proposed that the hypermobile first ray everted when dorsiflexed, and assumed that the hallux underwent the same motion. Inman (1974) and later D'Amico and Shuster (1979) demonstrated this concept using similar methodologies. Inman used pendulums while D'Amico and Shuster used pins glued to the toe nails of the hallux of their subjects. When the subtalar joint was moved from a neutral position to a pronated one, it was observed that the pendulums and pins internally rotated towards the midline of the body. Inman (1974) concluded that pronation of the foot "*imposes a longitudinal rotation on the first ray (metatarsal and phalanges)*". This statement implies that Inman (1974) considered the metatarsal and hallux to move as one unit. Wanivenhaus and Pretterklieber (1989) contended that pronation (eversion) of the hallux observed in hallux valgus was a compensation for the eversion in the first tarsometatarsal joint.

2.4.2.6 Discussion

Many inconsistencies exist in the literature, with a great deal of contradiction remaining, and still no common theory of aetiology has been agreed. This has been exacerbated by the use of differing methodologies and terminology.

Many authors report a higher prevalence of hallux valgus in females. This may be due to hormonal differences that exist between the genders and the harmful effects of female shoes. To the author's knowledge, only one study to date has observed hallux valgus from a purely genetic point of view (Johnston 1956). This study paid little attention to the predisposing factors linked with hallux valgus, e.g. relative metatarsal length. Such factors may themselves be genetically influenced.

From the evidence presented, it appears likely that genetic determination has a role in the actiology of hallux valgus. It is unknown whether the condition is directly inherited or is a secondary result of another genetically influenced factor. Further investigation is required to quantify the contribution of genetic influences to hallux valgus and these factors. Although hallux valgus could be the result of the expression of a single gene (Johnston 1956), it appears unlikely that this is the case. Indeed, very few single gene human traits have been identified. Deviation of the hallux on its metatarsal is present within the population in varying degrees; the clear-cut distinction of deviated or not that one should normally attribute to the segregation of a single gene is not observed. Moreover, since environment (footwear) is believed to be significant in the development of the deformity, the proposed pattern of inheritance must be considered multifactorial. Multifactorial traits are those that involve two or more genes and are strongly influenced by the environment (Cummings 1993).

There seems little doubt that shoes are at least a contributing factor in the actiology of hallux valgus. All studies comparing barefooted with shoe wearing populations show a significant correlation between the use of footwear and hallux valgus. However, the most striking observation is that non-shoewearing populations do have some prevalence of hallux valgus. The prevalence of hallux valgus within the unshod populations appears to vary markedly. An association between hallux valgus and the use of footwear evidently exists. However, hallux valgus does not occur in every person who wears shoes or, indeed, in the vast majority of the shoewearing population. The design and fit of the footwear habitually worn may be significant, but since the condition has been observed in non-shoe wearing populations, it is possible that the initiation of the destructive process is the result of factors other than footwear and that shoes merely exacerbate an already present deformity. Clearly, such factors may be of genetic origin e.g. inherited ligamentous laxity.

The underlying cause of many forefoot problems, including hallux valgus, has been assumed to be excessive pronation of the subtalar joint. Whether forefoot deformity initiates rearfoot and midfoot collapse or is the result of rearfoot and midfoot malfunction has caused much speculation. The significance of pronation lies in its effect on the first ray. Subtalar joint pronation is believed to

"unlock" the midtarsal joint complex, rendering the first ray hypermobile and furthermore, subject to deforming ground reaction forces and trauma from environmental stimuli such as footwear.

It has been hypothesised that subtalar and midtarsal joint pronation may precipitate an increase in the angle of gait (Miller 1960). This angle is effectively responsible for the alignment of the hallux, with respect to the direction of progression during ambulation. The average angle of gait causes the hallux to be mildly abducted from the line of progression. In feet that gradually adopt a pronated attitude the forefoot is observed to abduct at the midtarsal joint inducing a concurrent increase in the angle of gait. Consequently, the hallux functions in a more abducted attitude. This allows propulsion to occur through the medial border of the hallux rather than through its apex. Callous formation on the medial border of the proximal inter-phalangeal joint of the great toe is frequently observed as evidence of this. Due to pronation, the first ray is hypermobile and thus may be influenced by a combination of anterior-posterior shear forces and vertical forces. The resultant force may act to displace the hallux towards the lesser digits, theoretically, producing or increasing the deforming stress acting upon the 1st MPJ.

Johnston (1956) and later Greenberg (1979) and Kilmartin and Wallace (1994), found little evidence to support an association between the two deformities. Thus, it is questionable whether pronation is linked with hallux valgus. Conversely, it is possible that hallux valgus is a result of rearfoot/midfoot dysfunction. However, there is no more evidence to support this than for any of the other possible actiologies.

The subject of first metatarsal length and its effect on forefoot function has for many years commanded interest. The review of the literature presented here shows that a state of confusion is apparent; much contradiction exists between authors regarding whether a longer first metatarsal is significant in the actiology of hallux valgus. These inconsistencies are partly the result of different methodology. The author considers first metatarsal protrusion to be potentially important in the pathomechanics of subluxation of the 1st MPJ for the following reasons. First metatarsal protrusion augments the lever arm of the first digit: the longer the protrusion, the greater the lever arm. A deviated hallux in contact with the second toe will, therefore, be at a mechanical advantage over the buttressing effect of the second digit; therefore the second digit will have a diminished stabilizing effect on the hallux.

Furthermore, as the length of the lever arm increases, the restraining ability of the metatarsal cuneiform joint to oppose metatarsal adduction is decreased. Thus the hallux will adduct the first metatarsal with less resistance.

It is conceivable that relative metatarsal length is determined genetically, analogously to height and body stature. However a review of the literature revealed no empirical evidence of this.

The actiology of hallux valgus is uncertain. Only by further research will the cause, or causes, of the deformity be established. The presented evidence suggests that several factors may be important in the development of hallux valgus. It is possible that one or more of these factors may have a genetic origin. However, environment (footwear) also appears to play an important role in the actiology.

The information gleaned from this review of literature allows a preliminary model for the actiology of hallux valgus to be developed. This model is presented in the following section.

CHAPTER III

METHODS

3.1 Introduction.

From the information presented in Chapter II it is possible to propose a descriptive clinical model that relates the degree of lateral deviation of the hallux at the 1st MPJ (and thus, hallux valgus) to several clinical factors proposed as significant in the actiology of hallux valgus. The mathematical development of this model is possible. Clinical measurement techniques for the factors are first identified and applied to a suitable sample. Performing appropriate statistical analyses on the data from this sample provides specific parameter values for the model. Once the model has been refined to mathematical form it is potentially very useful, providing the clinician with a method of identifying individuals at risk of developing hallux valgus.

This chapter first presents the descriptive clinical model (Section 3.2). Following this a literature review is undertaken to identify and select suitable methods of measurement for the factors under investigation within this study. Literature was examined for evidence of each method's validity. In cases where insufficient information were available concerning a measurement techniques validity, experiments to test the methods validity were conducted (Section 3.3). The repeatability of all methods were tested experimentally and the results of these experiments presented (Section 3.3). Consideration is then given to the type of sample required to yield suitable data for the mathematical development of the model. The methods used to generate this sample are described (Section 3.4). The process of data analysis and the statistical techniques applied to the data are described in Section 3.5.

3.2 Descriptive Clinical Model.

All factors are initially assumed to be of equal significance in determining 1st MPJ angle (and thus hallux valgus), since there is no evidence from the literature to suggest that a hierarchy exists within the proposed, predisposing factors. All foot measurement parameters are partitioned into genetic and environmental components, since all have the potential to be determined by a combination of genetic and environmental influences. Given this and the evidence presented in Chapter II, the following clinical model of aetiology may be proposed:

(Equation 3.1)

$$(1^{st}\ \text{MPJ angle}_G,\ 1^{st}\ \text{MPJ angle}_E) = \int (AP_G, AP_E), (MP_G, MP_E), (DP_G, DP_E), (PRNP_G, PRNP_E), (O_G, O_E)$$

, S, A

Where:
$_G$ = Genotype
$_E$ = Environment (all non-genetic factors)
AP= Abnormal pronation
MP= 1st metatarsal protrusion
DP= 1st digit protrusion
PRNP =Plantarflexed first ray neutral position
O= Other known and unknown factors
S= Gender
A= Age

The above model suggests that the 1st MPJ angle is due to a function of all of the factors under investigation in this study with the addition of a component labelled "O" which represents all other possible causes.

3.3 Clinical Measurement Techniques.

To refine the model presented in Section 3.2 to mathematical form and test its ability to predict 1st MPJ angle, suitable methods of measurement for the factors under investigation had to be identified prior to the collection of data. The requirements of these techniques were that they were valid, accurate and unbiased methods of assessment for the variables under investigation. Furthermore, in order to develop a model that may be applied by the clinician in identifying individuals at risk of developing hallux valgus, the methods needed to be simple, non-invasive, repeatable, inexpensive and quick to carry out. A review of pertinent literature was carried out in an attempt to identify such techniques.

3.3.1 Measurement of first Metatarsophalangeal Joint Angle.

The deviation of the hallux on its metatarsal is commonly used as a measure of hallux valgus and is termed the 1st MPJ angle. X-ray charting of 1st MPJ angle is frequently used in the preoperative assessment of hallux valgus (Kilmartin Barrington and Wallace 1992). The repeatability of the radiographic technique has been shown (Fox and Firshein 1989, Kilmartin, Barrington and Wallace 1992). However, since radiographic equipment is costly and requires specialised training to use, and the exposure of clinically normal subjects to ionising radiation cannot be ethically justified, its use within the development of the model would place considerable limitations upon the models clinical application. A clinical alternative was sought. In published research, two clinical methods of assessment of this variable have commonly been used: goniometric measurement (Kilmartin and Bishop 1988, Kilmartin and Wallace 1992) and footprint analysis (Barnicot and Hardy 1955, Ross 1986, Sanders et al. 1992).

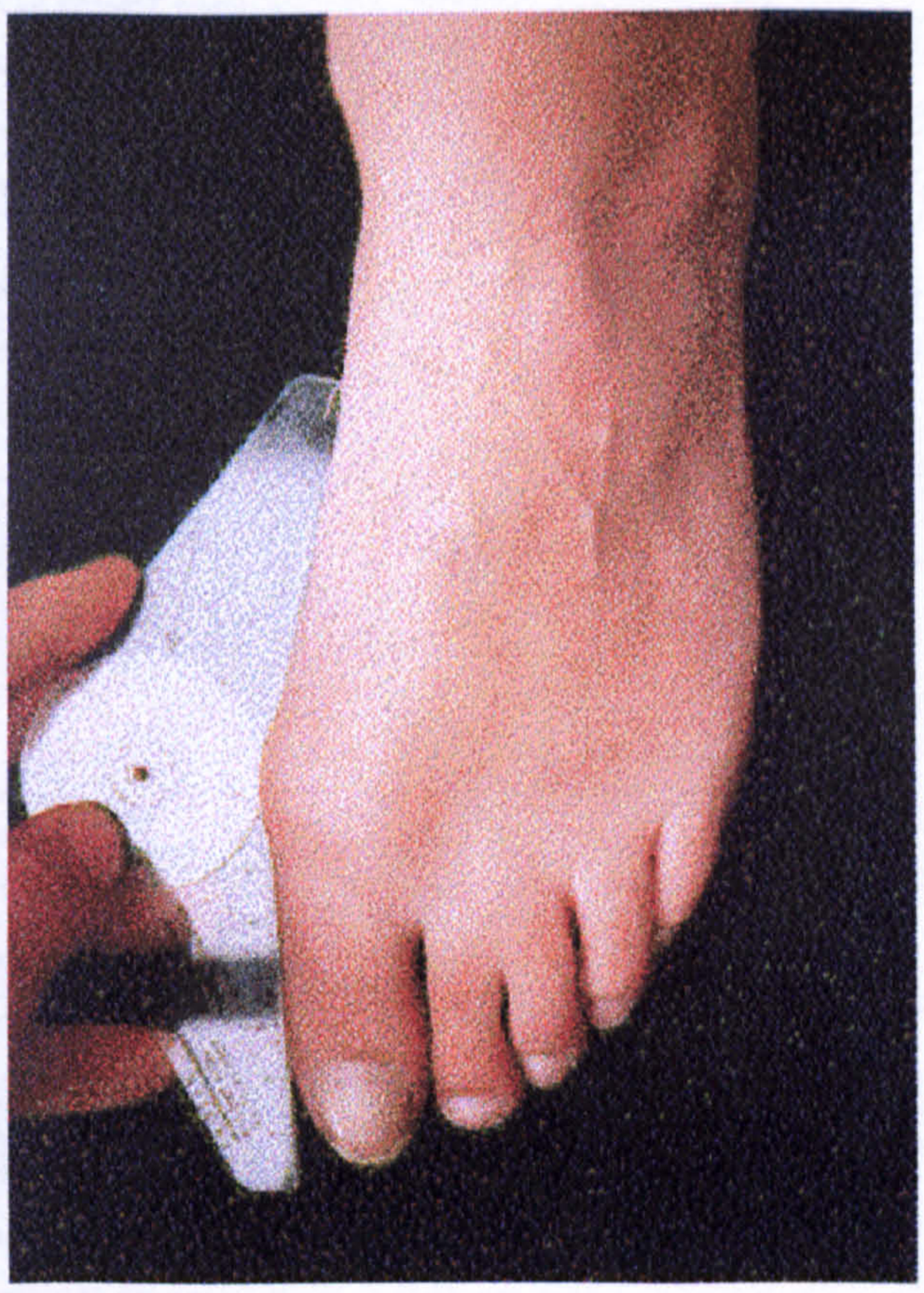
The validity of goniometric measurement was demonstrated by Kilmartin and Wallace (1992) A strong linear relationship was observed between goniometric and X-ray data ($r = 0.75$, $r^2 = 0.56$) in 58 school children. It was concluded that the goniometric technique provided valid measurements of 1st MPJ abduction.

Barnicott and Hardy (1956) and, later, Sanders et al. (1992) demonstrated that footprinting techniques provided valid measurements of 1st MPJ angles. Again, comparisons with X-ray data were made, Barnicott and Hardy (1956) reporting a correlation of r= 0.51 (r^2=0.26) and Sanders et al. (1992) reporting a rank correlation of 0.9 (11 subjects).

The author was familiar with both techniques described. The goniometric technique is far quicker and easier to carry out than the analysis of footprints. Moreover, since the footprinting technique only provides details of the portion of the foot in contact with the ground and the medial border of the 1st MPJ is curved, and commonly not in contact with the ground, it is likely that this technique will provide inadequate measures of 1st MPJ angle. Given the evidence provided, the goniometric technique was adopted for use in this study.

Measurements of the subjects 1st MPJ angles were performed using the Kilmartin Finger Goniometer. The method described by Kilmartin and Bishop (1988) was applied: the subjects were positioned standing erect on a hard flat surface. The mid-line of the medial surface of the hallux was visually identified and one arm of the finger goniometer was positioned against it. Locating the hinge of the goniometer directly over the 1st MPJ, the remaining arm was then brought up against the mid-line of the medial surface of the first metatarsal shaft. The goniometer was maintained parallel with the transverse plane. A reading was recorded from the goniometer scale (degrees) (Figure 3.1). 1st MPJ angles <15° were considered to be within normal limits, while 1st MPJ angles ≥15° were considered to be abnormal and thus, hallux valgus.

Figure 3.1: Measurement of the 1st MPJ angle using the Kilmartin finger goniometer.



3.3.2 Measurement of Foot Pronation.

The subtalar joint converts linear forces (e.g. ground reaction force, and muscular contractile force) into rotational forces or moments. These moments act about the subtalar joint axis to produce the triplanar motions of pronation and supination, dependent on their position about the joint axis. Equilibrium of the subtalar joint exists when the sum of the moments acting across the joint axis is equal to zero (Kirby 1987). The relaxed calcaneal stance position of an individual is the position of rotational equilibrium about the subtalar joint axis for the given individual in this position. The terms flat foot or pes planus are frequently used to describe the foot that is excessively pronated when in relaxed calcaneal stance. Since abnormal rearfoot pronation results in a downwards and medial displacement of the head of the talus, navicular and first cuneiform, a lowering of the medial longitudinal arch and consequential flattening of the foot is observed (Otman et al, 1988).

Efforts to establish an accurate method of measuring foot pronation have received considerable attention (Davidson 1970). Measurements obtained from charted dorsoplantar and lateral radiographs have commonly been applied as measures of pronation. However, methodological differences have led to ambiguous results. In the absence of radiographic techniques, goniometry and footprint analysis have been employed. The use of X-ray techniques would have placed considerable limitations on the model's clinical application and were therefore not considered for use. Thus, the following discussion focuses on the reliability and validity of goniometric and footprinting techniques in the analysis of foot pronation, in an attempt to identify a suitable method of measurement for use within the study.

The triplanar motion of pronation is predominantly observable as the frontal plane motion eversion at the subtalar joint. Thus, the measurement of calcaneal alignment in the frontal plane during relaxed calcaneal stance has been widely used as means of measuring excessive foot pronation (Thomson 1994). However, the repeatability and validity of this technique are questionable. Menz (1995) states: *"...there is a disturbing lack of reliability in hindfoot measurement"*.

Both non-weightbearing and weightbearing assessment techniques have been employed. Common to both techniques has been the use of subtalar joint neutral as a reference point. Subtalar joint neutral was defined by Root et al. (1977) as the position in which the joint is neither pronated nor supinated. They suggest that by everting the calcaneus two-thirds from its maximally inverted position the neutral position may be calculated. The validity of this technique relies on the existence of the perfect 2:1 ratio of supination to pronation at the subtalar joint described by Root et al. (1977). However, it is well established that within the population positional variations in the deviation of the subtalar joint axis exist (Manter 1941, Root et al. 1966, Isman and Inman 1969). Isman and Inman (1969) showed that the distribution of range of motion between inversion, eversion, adduction, abduction, plantarflexion and dorsiflexion available at the subtalar joint is dependent on the axial position. Clearly, variations in the position of the subtalar joint axis will result in a departure from this 2:1 ratio. However, the most common approach employed to identify subtalar joint neutral is palpation of the talar head for osseous congruency (Menz 1995). This technique may be applied with the subject both non-weightbearing and weightbearing. Significant differences in subtalar joint pronation have been identified following the

transition from non-weightbearing to weightbearing. Lattanza et al. (1988) noted that calcaneal eversion increased by 37% following the transition to weightbearing. Thus, it seems likely that non-weightbearing assessment of subtalar joint pronation yields significantly underestimated measures. Moreover, since the foot primarily functions bearing weight, the study of foot pronation in a non-weightbearing position seems of little significance. Thus, weightbearing assessment is of greater relevance.

On weightbearing, the relaxed calcaneal stance position is measured (in degrees) in the frontal plane, relative to the supporting surface. This is compared to the neutral calcaneal stance position, similarly measured, relative to the supporting surface. Neutral calcaneal stance position is the expression of subtalar joint neutral when the foot is weightbearing (Menz 1995). Clinical identification of these positions requires the accurate identification and marking of a bisection of the posterior aspect of the heel. Menz (1995) suggests that the potential for error in this marking is high, the thickness and length of the line drawn being highly significant to the results obtained. Moreover, Elveru et al. (1988) contend that the movement of skin and soft tissues over the retro calcaneal area is so significant that no surface marking can represent a bisection of the calcaneus. Indeed, Maslen and Ackland (1994) radiographically studied the displacement of skin markers in the foot and reported that, although accurate location of skin markings was possible, upon movement of the foot the relationship between skin and skeletal markings deteriorated. They contend that this was exacerbated by the short segment lengths involved. Menz (1995) suggests that quantification of soft tissue displacement is virtually impossible due to anatomical variations between individuals.

The validity of frontal plane goniometric measurement as a measure of foot pronation must be questioned considering the evidence presented. Clearly, the validity of the technique is dependent upon the accurate identification of subtalar joint neutral and the validity of skin markings. The accuracy of both factors is highly questionable. Evidently, the goniometric measurement of rearfoot position as an inference of foot pronation may be too subjective for use within the study. The reliability of skin markings and the validity of frontal plane measurement as a complete measure of pronation must be evaluated by further research. Subtalar joint axial variation is present within the population (Isman and

Inman 1969). Thus, the relative importance of the frontal plane component of pronation is also likely to vary between individuals. Indeed, Pressman (1987) contended that pes planus may exist without calcaneal eversion. Clearly, to base a measure of pronation on measurements of the frontal plane component alone may be unwise.

Since the 1930's, the height of the medial longitudinal arch, and thus the amount of foot pronation, has been indirectly measured using arch height index systems (AHI), charted on footprints, obtained from inked rubber mats (McCrory et al. 1997). A review of the literature illustrates that the validity of AHI's when used to infer the level of arch height is a contentious issue (Cobey and Sela 1981, Hawes et al. 1992).

Hawes et al. (1992) contend that AHI's are poor predictors of arch height and conclude that the use of footprint parameters are not valid as measures of height of the medial longitudinal arch. The conclusions of these workers are in strong contrast to the results reported by Irwan (1937) and McCrory et al. (1997) who present strong correlation's between direct measures of arch height and AHI. From the analysis of 100 footprints, Irwan (1937) reported a reliability coefficient of $r=0.98$ ($r^2=0.96$). McCrory et al. (1997) analysed footprints and weightbearing lateral radiographs of 14 women and 31 men. The authors report a correlation of $r=0.67$ ($r^2=0.45$) between arch height index and navicular height. When navicular height was normalised to foot length a correlation of $r=0.71$ ($r^2=0.50$) was yielded. The authors conclude that arch height index provide useful indirect measurements of medial longitudinal arch height.

Thomson (1994) investigated the validity of AHI in a comparative study of AHI and frontal plane goniometric measurements of relaxed calcaneal stance. Thomson (1994) concluded that valgus index is a useful measure of hindfoot position, being less judgmental and possibly more sensitive to small amounts of rearfoot deviation than frontal plane measurements. Several workers who have demonstrated excellent correlation coefficients for the calculation of AHI from footprint data echo these views. Indeed, many authors suggest that structural characteristics of the arch can be assessed from the analysis of footprints, with decreasing AHI mirroring increases in the height of the medial

longitudinal arch (Schwartz et al. 1928, Clarke 1933, Cureton et al. 1935, Irwin 1937, Cavanagh and Rodgers 1987, McCrory et al. 1997).

Excepting radiography, no one method for assessing the height of the medial longitudinal arch has been more widely accepted than the charting of footprints and the calculation of AHI. Thus, given the evidence, AHI values of footprints clearly remain useful research tools. Therefore, foot pronation was measured using an AHI within this study.

Measurement of AHI were obtained from footprint data collected using the Berkemann Pedograph footprinting system. The following method was applied.

3.3.2.1 Footprint Data Collection

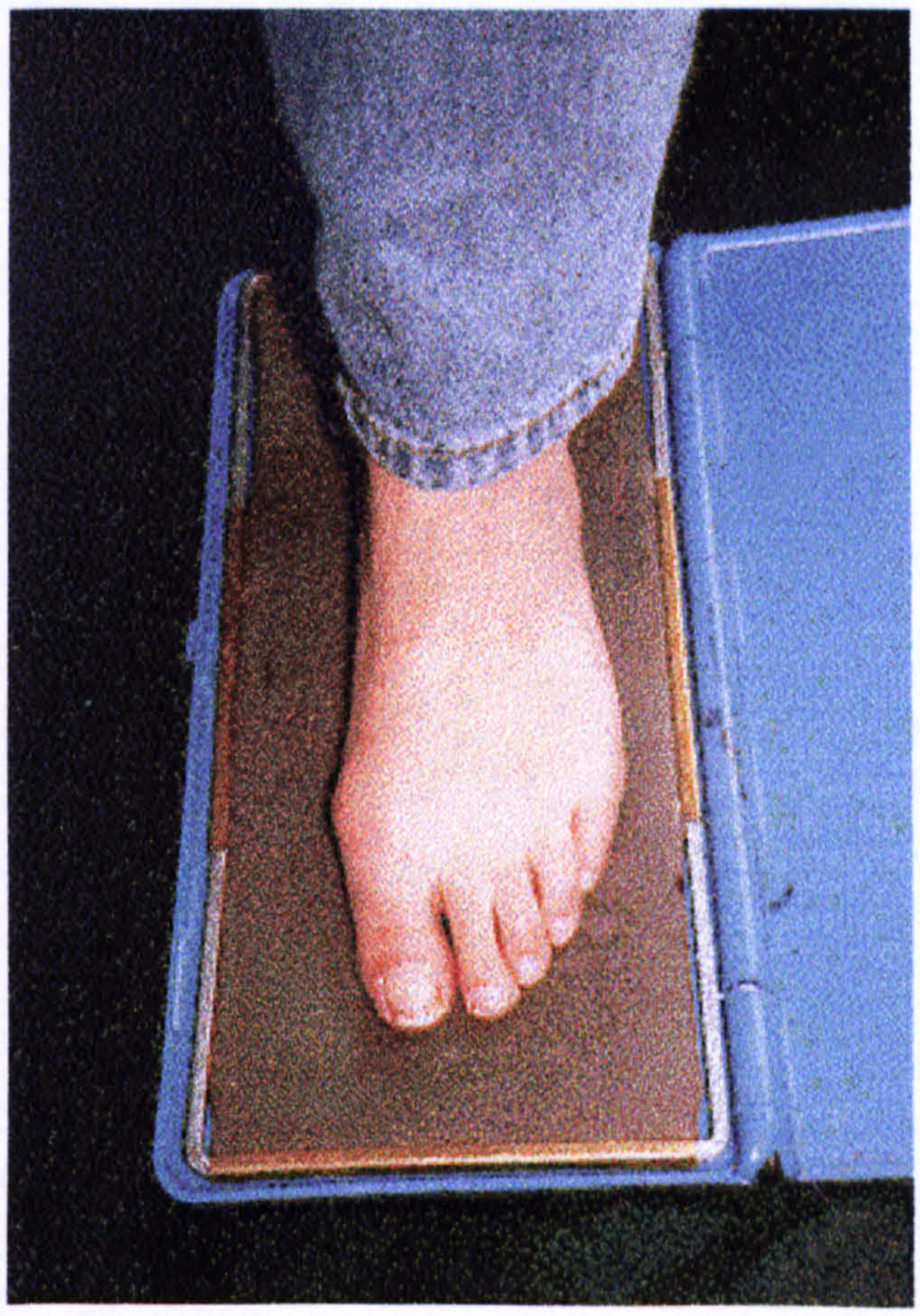
The underside of the rubber membrane of the Berkemann Pedograph was lightly inked using the felt roller and the paper positioned beneath it. The subject adopted an upright position of stance. The subject was then requested to elevate the foot being examined so that the footprinting mat could be positioned beneath. This achieved, the subject was requested to place the foot onto the mat. Targeting of a point on the wall opposite by the subject was carried out in an attempt to reduce postural sway. The subject then removed their foot, stepping backwards off the mat (Figure 3.2). Each footprint was checked before the data was accepted. Criteria for inclusion were:

i. The whole footprint must be included; if any part was absent, the print was rejected and another footprint was generated.

ii. The footprint must be clear and not smudged; any smudged prints were rejected and a replacement produced.

This process was repeated for both feet.

Figure 3.2: Collection of footprint data using the Berkemann pedograph. The under surface of the rubber membrane is lightly inked and a piece of paper is positioned beneath it to record the contact area of the foot.



3.3.2.2 Analysis of footprints

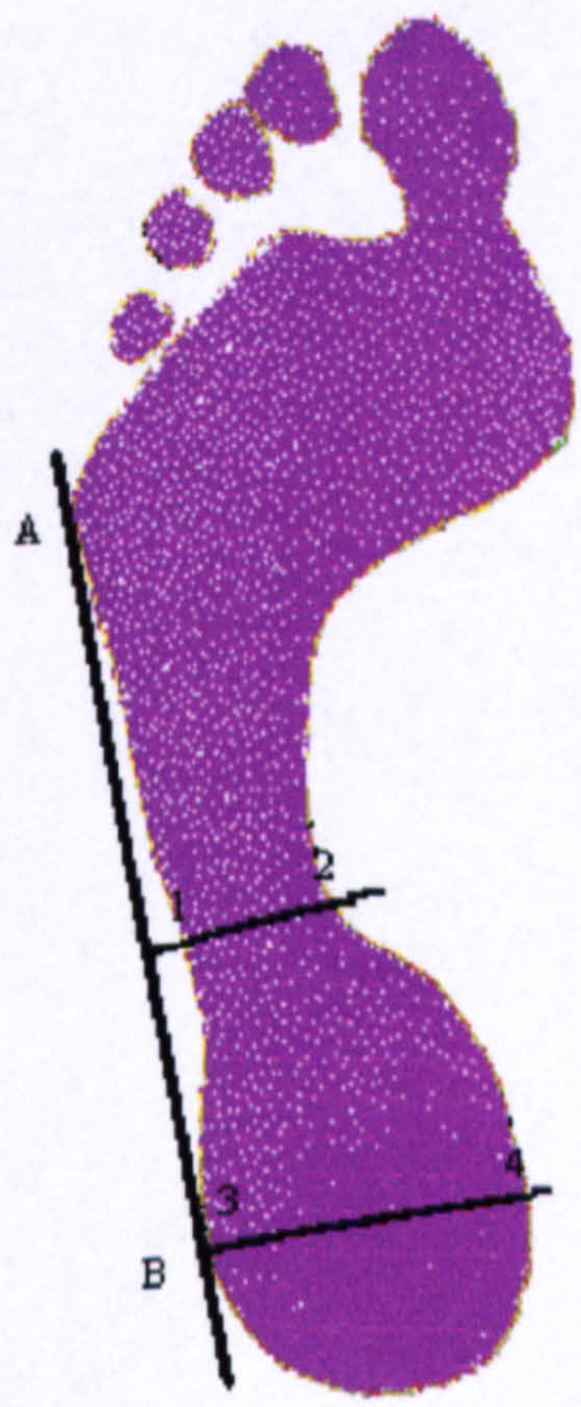
The method described by Rao and Joseph (1992) was used to chart the footprint for the calculation of AHI (Figure 3.3). A line was drawn between the most lateral aspect of the heel and the most lateral aspect of the metatarsal region and denoted as line AB. The narrowest region of the mid-foot area of the print was identified. A line was drawn perpendicular to line AB through this area. The points at which the line contacted the medial and lateral border of the print were identified and denoted as points 1 and 2 respectively. The distance between points 1 and 2 was measured using a rule and recorded. The widest region of the heel area was similarly identified and transected by a line drawn perpendicular to line AB. The points at which this line contacted the medial and lateral borders of the print were

identified and denoted as points 3 and 4. The distance between points 2 and 3 was measured using the rule and recorded. The AHI of the print was given by the equation:

(Equation 3.2)

Arch Height Index (AHI) = width of arch contact area /width of heel contact area

Figure 3.3: Demonstrating the method used to chart the footprints as described by Rao and Joseph (1992).



3.3.3 Determination of Metatarsal and Digital Formula.

Dorsoplantar X-rays have been used by many authors in an attempt to identify relative metatarsal length and to explain the association between this and foot pathology (Nilsonne 1930, Harris and Beath 1947, Hardy and Clapham 1952, LaPorta et al. 1974, Heden and Sorto 1981, Duke et al. 1982,). However, lack of standardisation of methodologies has led to contradiction in results. Since no

radiographic techniques were to be applied in the main study, an alternative assessment technique was sought. However, a review of literature revealed no alternative assessment of relative metatarsal and digital lengths.

Palpation techniques are frequently used in the clinical setting to identify the position of the metatarsal heads whilst weightbearing observation of digital patterning (in terms of distal protrusion) is used to determine digital formula. However, the validity of palpation and observation as methods of identifying the position of the metatarsal heads and digital patterning is uncertain. Thus, it was essential that the validity of these techniques was tested. Palpated and observed data were compared with the information obtained from radiographs.

3.3.3.1 Validation experiment

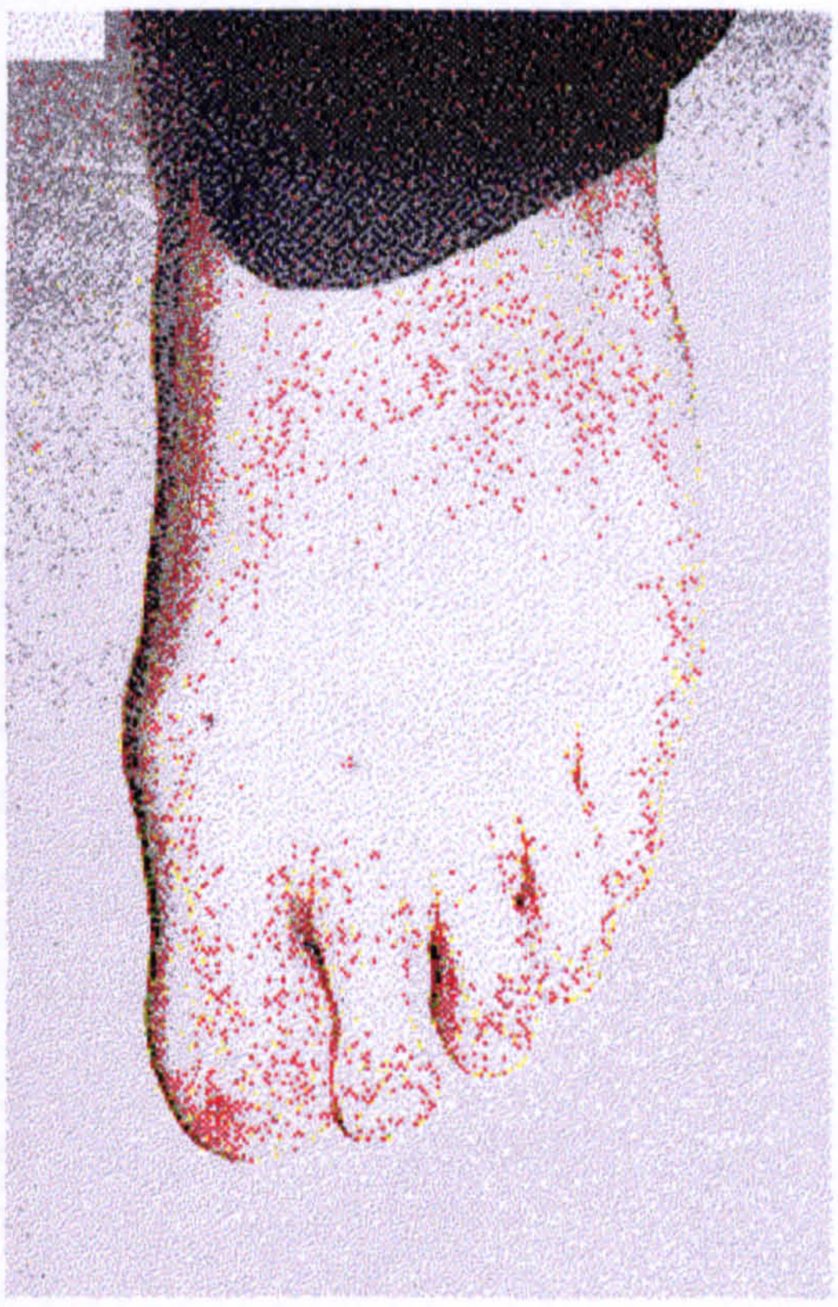
Thirty, Caucasian subjects of mixed gender (3 male, 27 female) were selected from the patient population of Northampton School of podiatry. All subjects had an available, weightbearing dorsoplantar X-ray of at least one of their feet. The mean age of subjects was 47 years (range= 30-74). Assessments were carried out over a period of two months.

Data obtained using clinical palpation was compared to available X-ray data.

3.3.3.2 Palpation and Observation Method

With the subjects standing on a hard, flat surface, the observer palpated the dorsal 1st MPJ area until the position of the distal most, palpable, aspect of the metatarsal head was identified. This point was then marked using a skin marking pen. This process was repeated on the 2nd MPJ. Individuals displaying a longer first metatarsal were coded 1; individuals with relative protrusion of the second metatarsal were coded as 0 (Figure 3.4).

Figure 3.4: Palpation was used to identify the position of the first and second metatarsal heads to determine metatarsal formula. Once identified the positions were marked. Individuals displaying a longer first metatarsal than second were awarded a metatatarsal formula of 1, individuals displaying a longer second metatarsal than first were awarded a metatarsal formula of 0. Observation of the distal protrusion of the first and second digits was used to identify digital formula. Similarly, protrusion of the hallux was awarded a score of 1, while protrusion of the second toe was awarded a score of 0.



With the subject weightbearing the distal protrusion of the first and second digits was observed. If the first digit protruded more distally than the second, a digital formula of 1 was awarded. If the second digit protruded more distally than the first a digital formula of 0 was awarded (Figure 3.4).

3.3.3.3 X-ray Method

To avoid observer bias, the subjects' details on each X-ray were obscured using masking tape and the X-rays shuffled to randomise their sequence. Graph paper was fixed over the X-rays using adhesive tape. The X-rays were illuminated from behind. The most distal aspect of the first and second

metatarsal heads were identified and marked on the graph paper using a ball-point pen. Similarly, the most distal point of the first and second digits were identified and marked on the graph paper. As before, individuals displaying a longer first metatarsal or digit were coded 1, individuals with relative protrusion of the second metatarsal / digit were coded as 0.

3.3.3.5 Statistical Analysis and Results

The results of the study are presented in Table 3.1

Table 3.1: Results of the validation experiment.

Subject	Metatarsal formula (palpated)	Metatarsal formula (x-ray)	Digital formula (observed)	Digital formula (x-ray)
1	1	1	1	1
2	1	1	1	1
3	1	1	0	0
4	1	1	1	1
5	0	0	0	0
6	0	1	0	0
7	0	0	1	0
8	1	1	1	1
9	0	0	0	0
10	0	0	0	0
11	1	0	1	1
12	1	1	1	1
13	1	1	1	1
14	0	0	0	0
15	0	0	0	1
16	1	1	1	1

17	1	1	1	1
18	0	0	0	0
19	1	1	0	0
20	0	0	0	0
21	0	0	0	0
22	1	1	1	1
23	1	1	1	1
24	0	0	0	0
25	0	0	0	0
26	0	0	0	0
27	0	0	1	1
28	1	1	0	0
29	1	1	1	1
30	1	1	1	1

From Table 3.1 it is clear that little difference exists in the results obtained using the palpation, observation and X-ray methods. However, to make sure that these results are not statistically different, data were analysed using the McNemar test . In this case, the McNemar test examines those cases with different values for palpated and x-ray assessment (See Section 3.6.2). If palpation is a valid method of assessment of metatarsal and digital formula, there should be no significant statistical difference between palpated and radiographic data. A level of statistical significance was set at P=0.05.

The results of these tests are given in Tables 3.2-3.3 Statistically significant differences are indicated by *:

Table 3.2: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between palpated and X-ray metatarsal formula dichotomous score data.

		Metatarsal formula dichotomous score X-ray data	
		0	1
Metatarsal formula dichotomous score	0	13	1
Palpated data	1	1	15
		n=30	(Binomial) 2-tailed P = 1.0000

Table 3.3: The results of non-parametric two-related sample McNemar test procedure; testing for differences between palpated and X-ray digital formula dichotomous score data.

		Digital formula dichotomous score X-ray data	
		0	1
Digital formula dichotomous score	0	14	1
Palpated data	1	1	14
		n=30	(Binomial) 2-tailed P = 1.0000

3.3.3.4 Discussion

The significance levels obtained exceeded the level set for statistical significance. The use of palpation and observation as a methods of determination of metatarsal and digital formula scores provides results which are not statistically different from the results obtained using radiographic techniques. Indeed, only 2/30 cases gave a different metatarsal and digital formula on palpation and observation than from X-ray data. In one of these cases palpation gave a score of 1 and X-ray gave a score of 0, in the other case this order was reversed. This shows that the palpation method is at least as accurate as the radiographic technique and must be considered valid as a method of determination of metatarsal and digital formula. Its use in this study is justified.

3.3.4 Measurement of First Ray Position.

Although Root et al. (1971) reported a qualitative assessment of first ray motion, to the author's knowledge at the time of this study the method described by Kilmartin, Wallace and Hill (1991) was the only reported quantitative method for the assessment of first ray neutral position (1st RNP). A measuring instrument developed by these workers, the Kilmartin Sagittal Raynger, measures in millimetres the amount of dorsiflexion and plantarflexion available in the first ray. The authors report the results of a repeatability study carried out on the instrument, correlation's of $r=0.69$ ($r^2=0.48$) and $r=0.78$ ($r^2=0.61$) ($n=360$) were reported for repeated measures of dorsiflexion and plantarflexion respectively. The validity of this technique is untested. However, in the absence of any other quantitative method of assessment for this variable, it was not possible to carry out a comparative study to test the validity of the technique.

In the absence of any other available quantitative assessment technique, the method described by Kilmartin, Wallace and Hill (1991) was selected for use in the study.

With the subject non-weightbearing, lying prone on a flat examination couch, palpation of the talar head allowed the subtalar joint to be positioned at a point approximating its neutral position. Application of load to the fifth metatarsal fully pronated the midtarsal joint. The subject's first ray was

moved through its full range of motion several times as a "warm up" before any measurements were taken. The measuring instrument, the Kilmartin Sagittal Raynger, was positioned below the metatarsophalangeal joints, with the movable quadrant located beneath the 1st MPJ. Holding the second, third, fourth and fifth metatarsal heads between the instruments fixed platform and the observer's forefinger the lesser rays were stabilised. The instrument's moveable quadrant was then used to push the head of the first metatarsal into maximal dorsiflexion. A measure of sagittal plane movement was recorded from the instruments' scale in millimetres. Pulling the head of the first metatarsal into maximal plantarflexion while it rested on the platform of the Sagittal Raynger's moveable quadrant allowed the amount of plantarflexory movement to be measured. Similarly, a measure of movement was recorded from the instrument's scale. The 1st RNP was calculated in millimetres, by subtracting the largest range of motion from the smallest and dividing by two (Figure 3.5).

3.4.2 Statistical Analysis and Results

Graphical representation of the data collected is given in Figures 3.6-3.25.

Figure 3.6: Distribution of 1st MPJ angle data left foot initial measurements

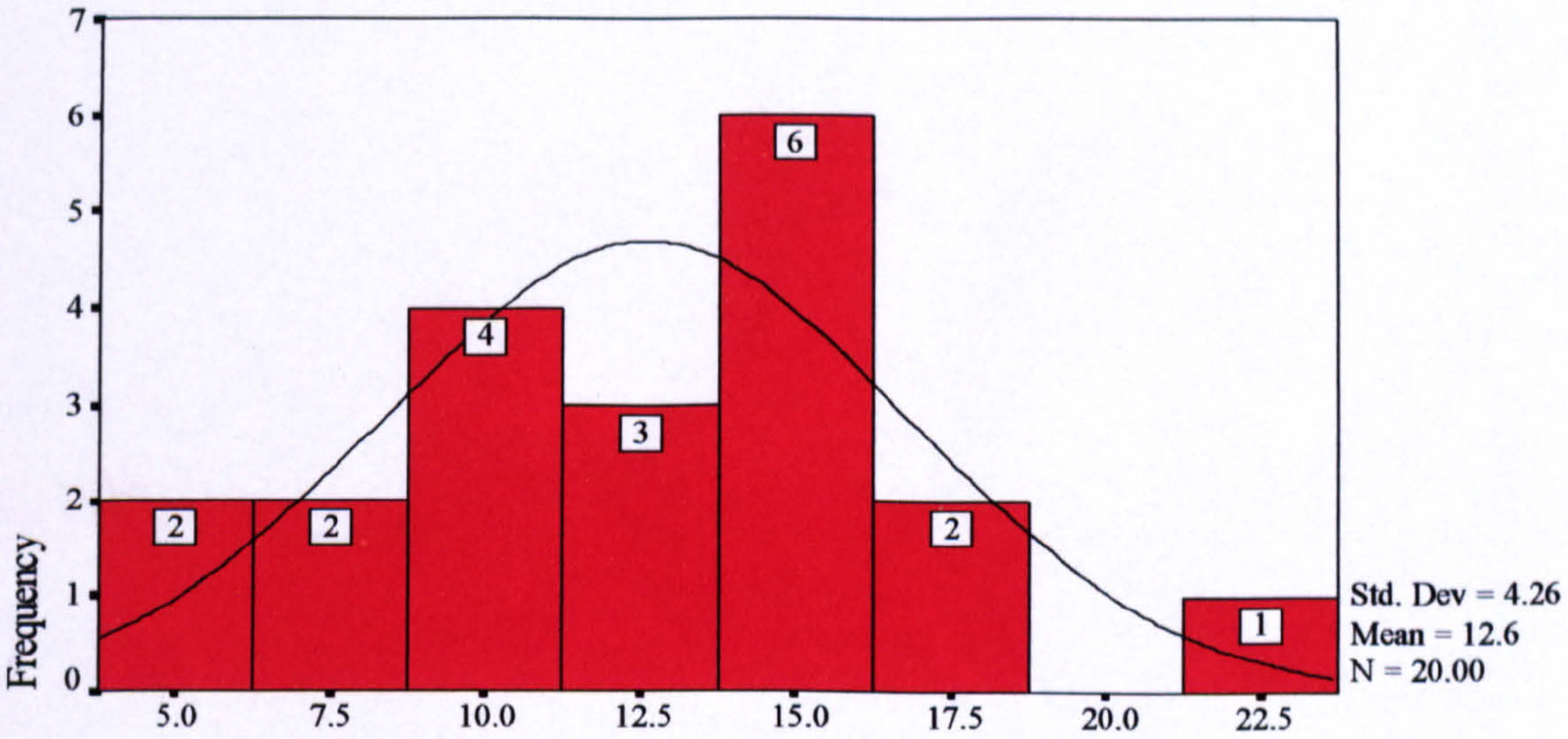


Figure 3.7: Distribution of 1st MPJ angle data right foot initial measurements

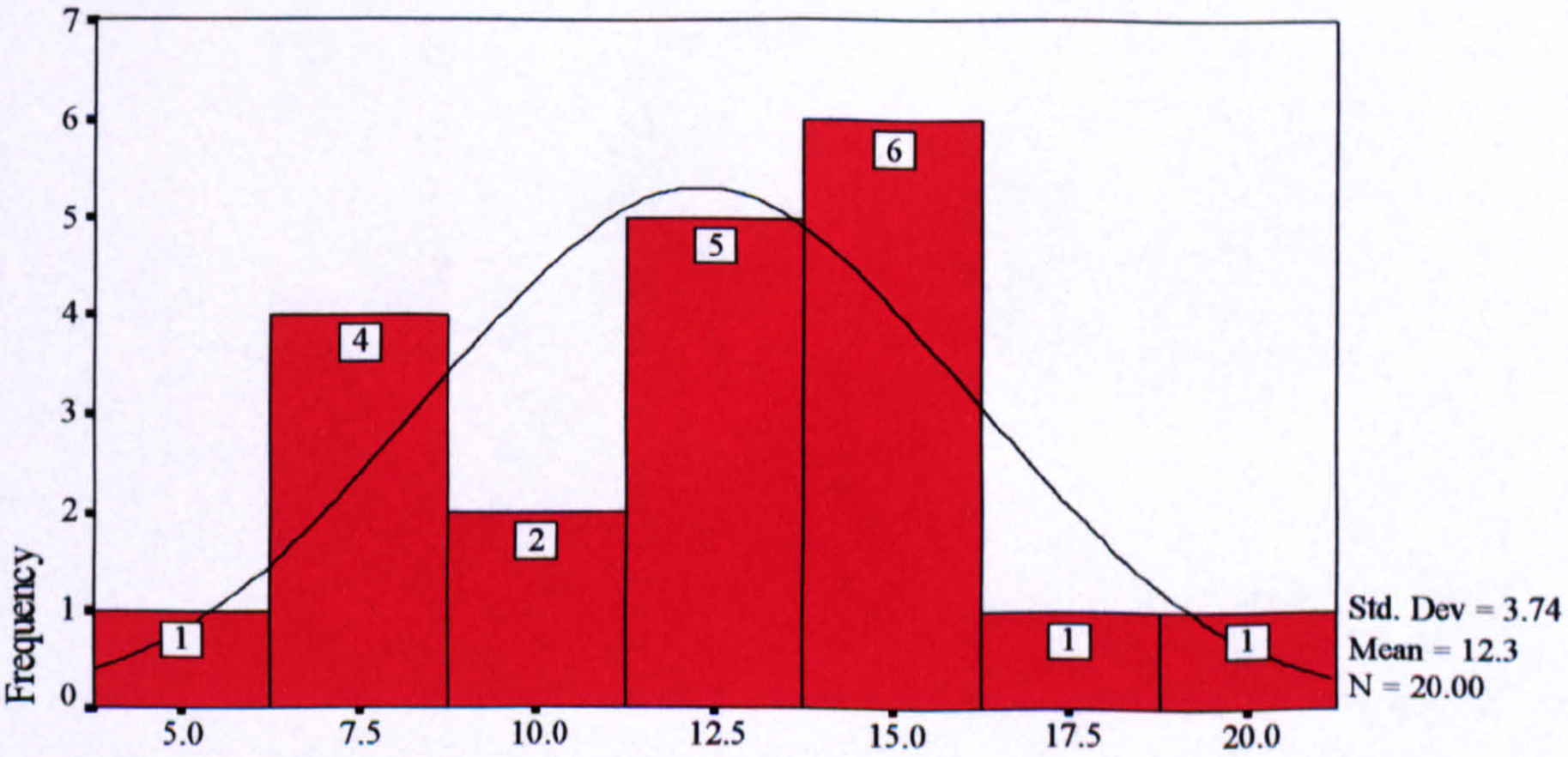


Figure 3.8: Distribution of 1st MPJ angle data
left foot second measurements

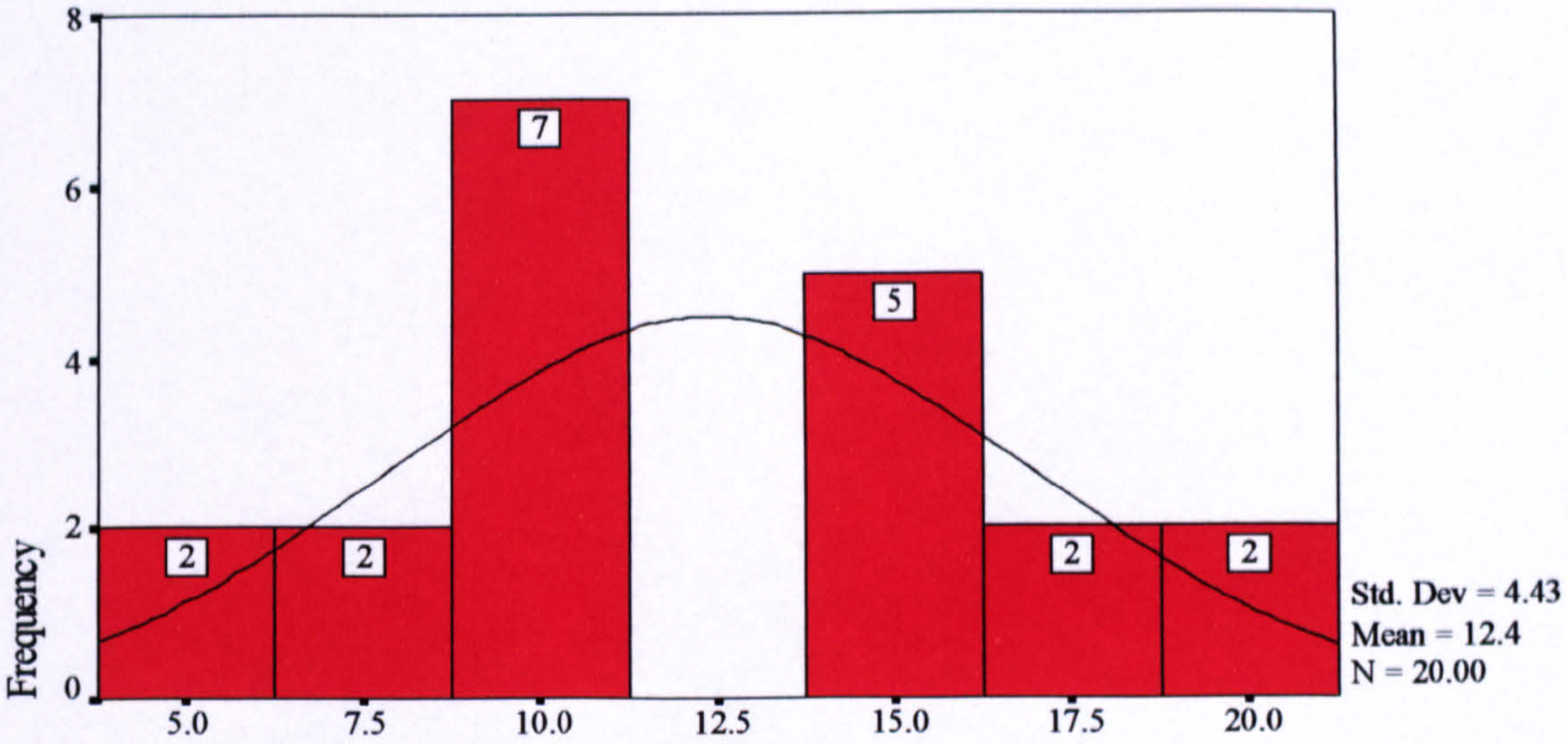


Figure 3.9 Distribution of 1st MPJ angle data
right foot second measurements

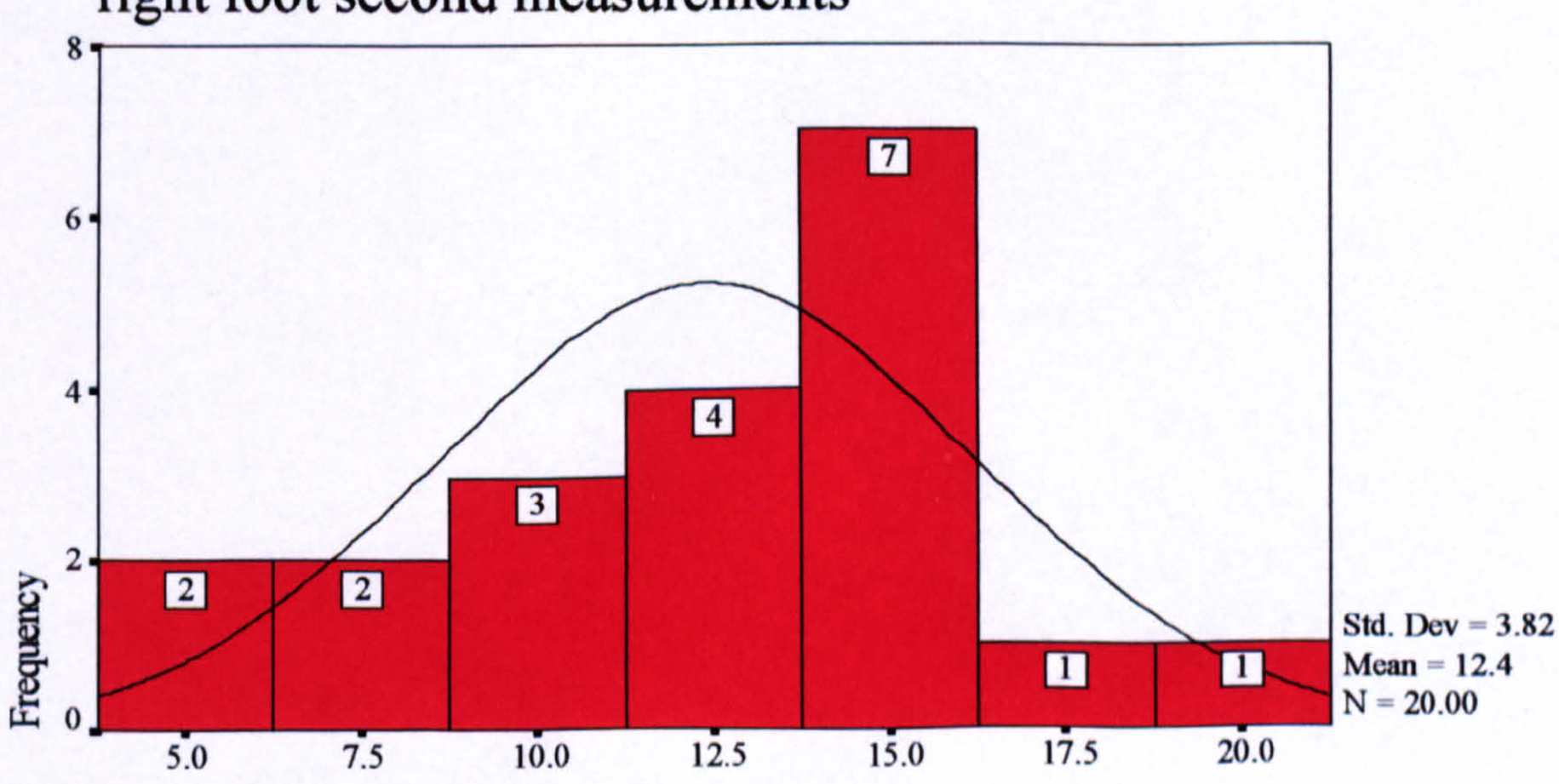


Figure 3.10: Distribution of arch height index data left foot initial measurements

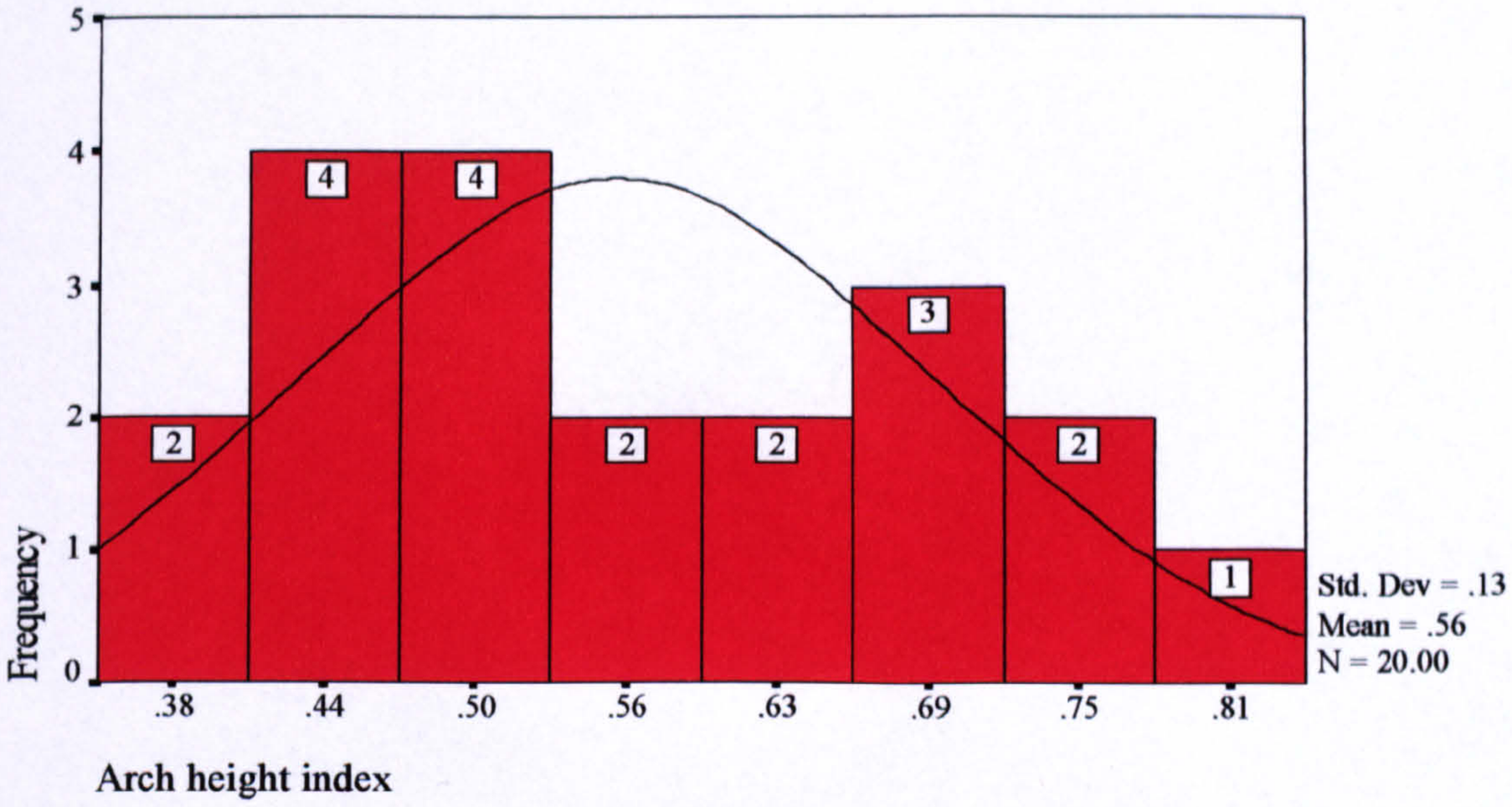


Figure 3.11: Distribution of arch height index data right foot initial measurements

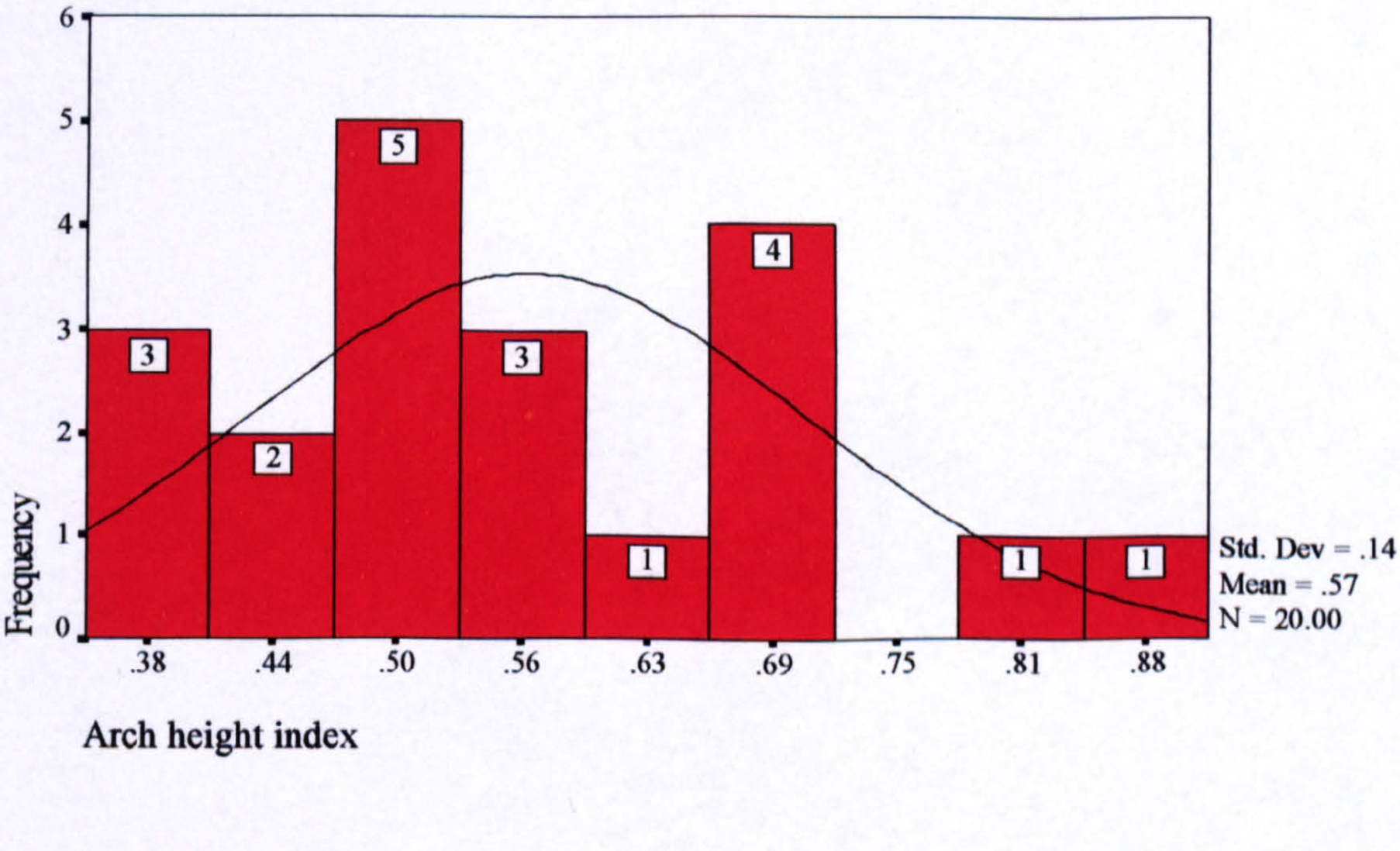


Figure 3.12: Distribution of arch height index data left foot second measurements

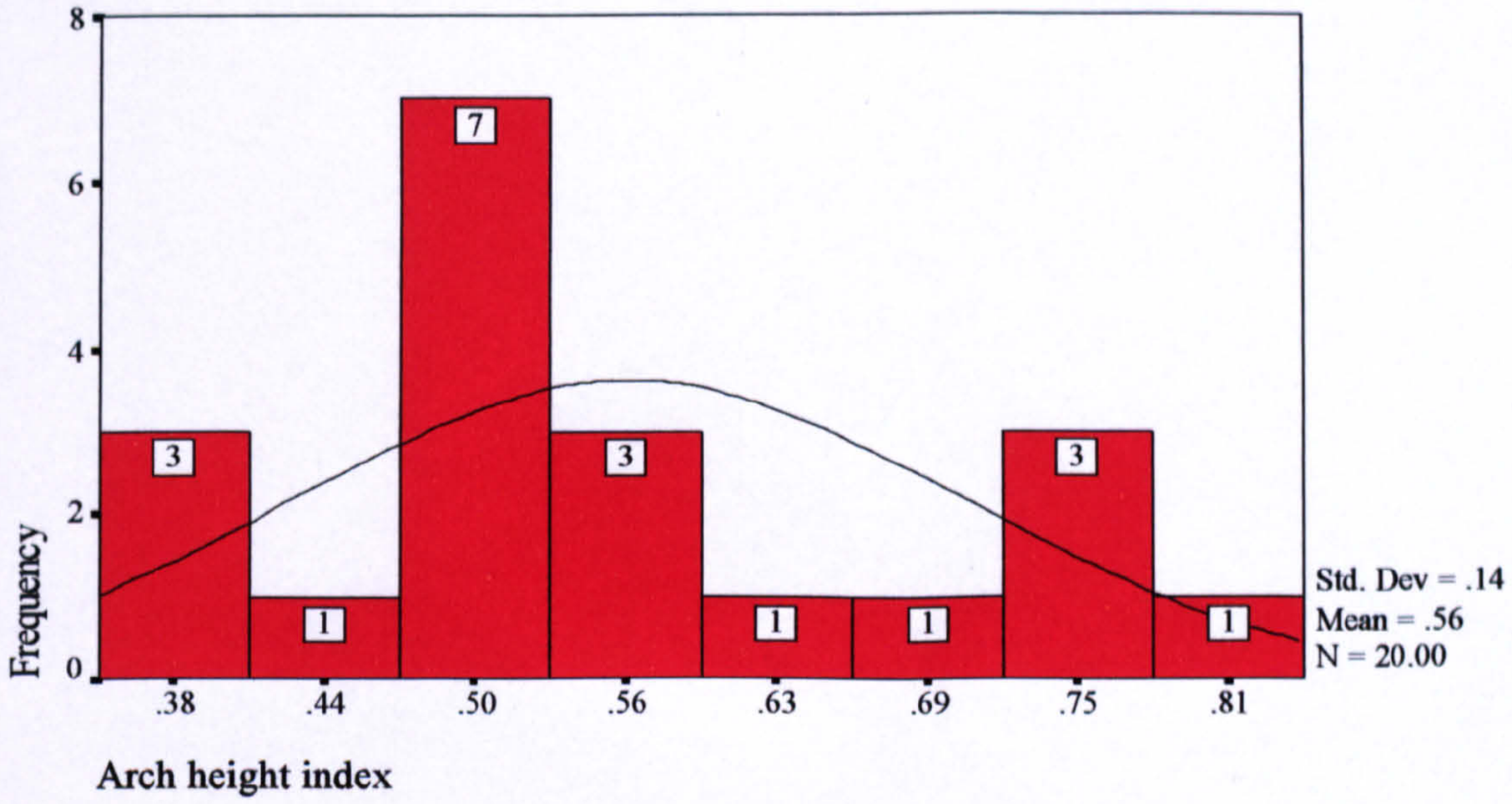


Figure 3.13: Distribution of arch height index data right foot second measurements

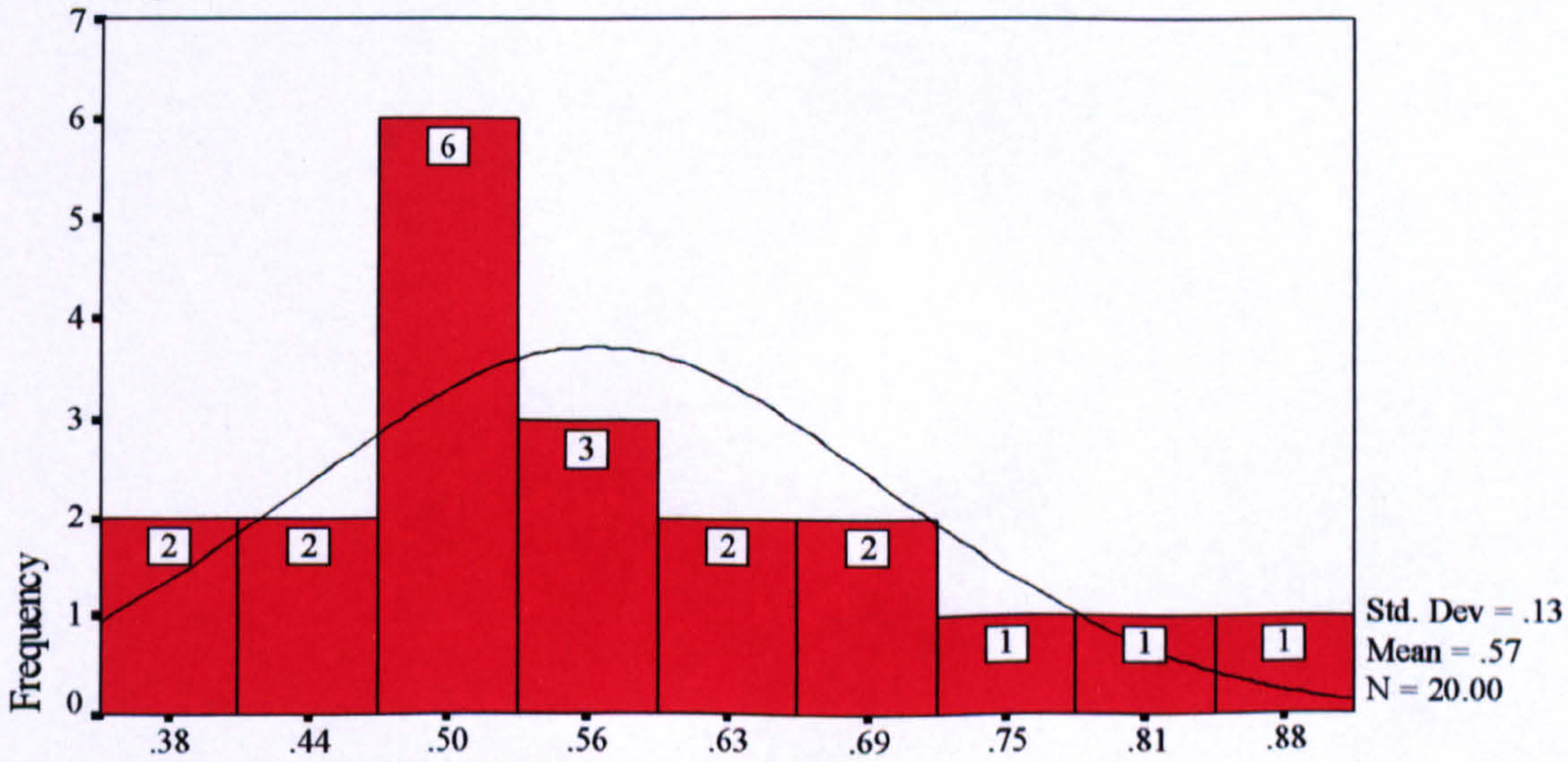


Figure 3.14: Distribution of 1st ray neutral position data left foot initial measurements

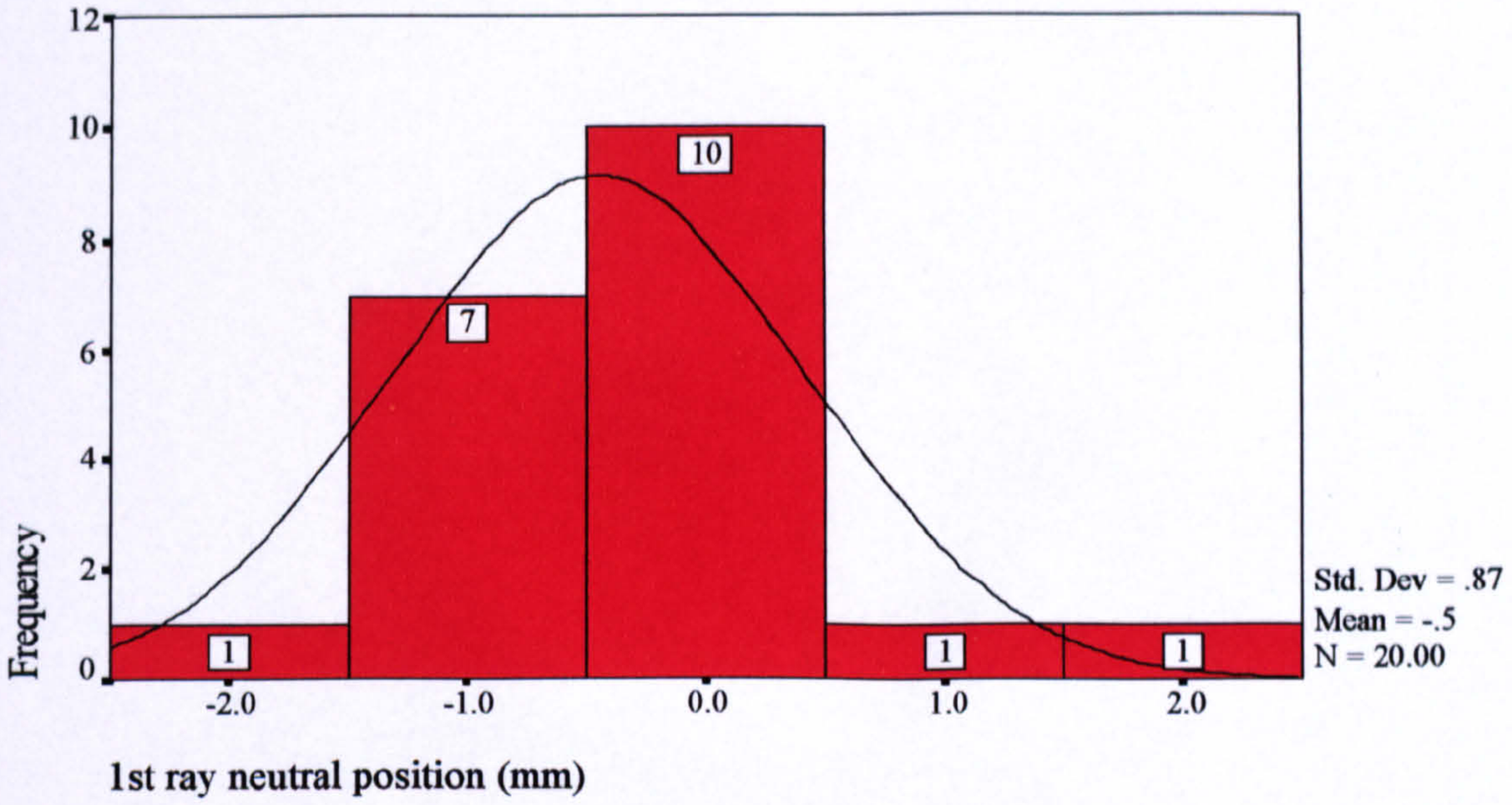


Figure 3.15: Distribution of 1st ray neutral position data right foot initial measurements

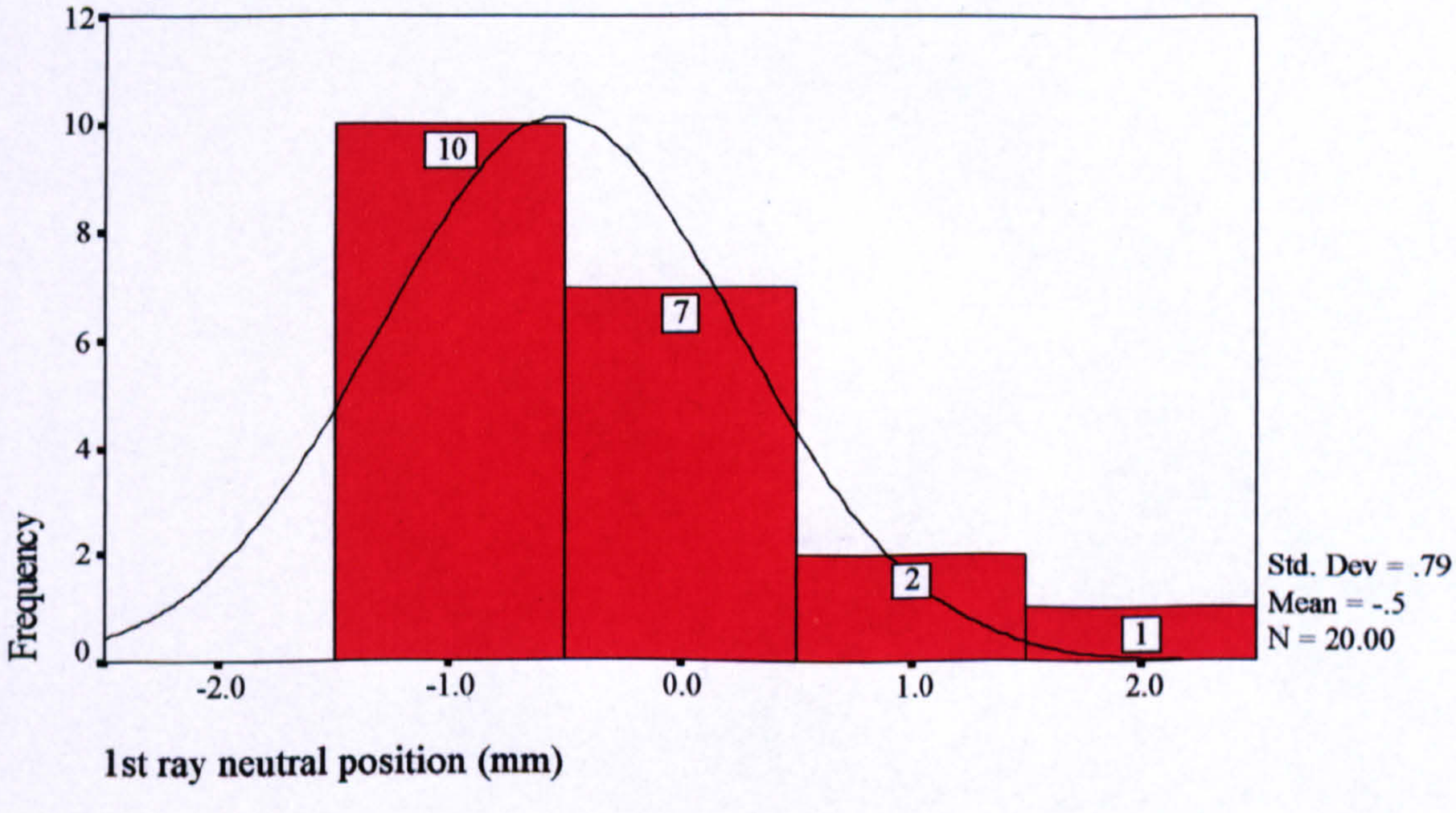


Figure 3.16: Distribution of 1st ray neutral position data left foot second measurements

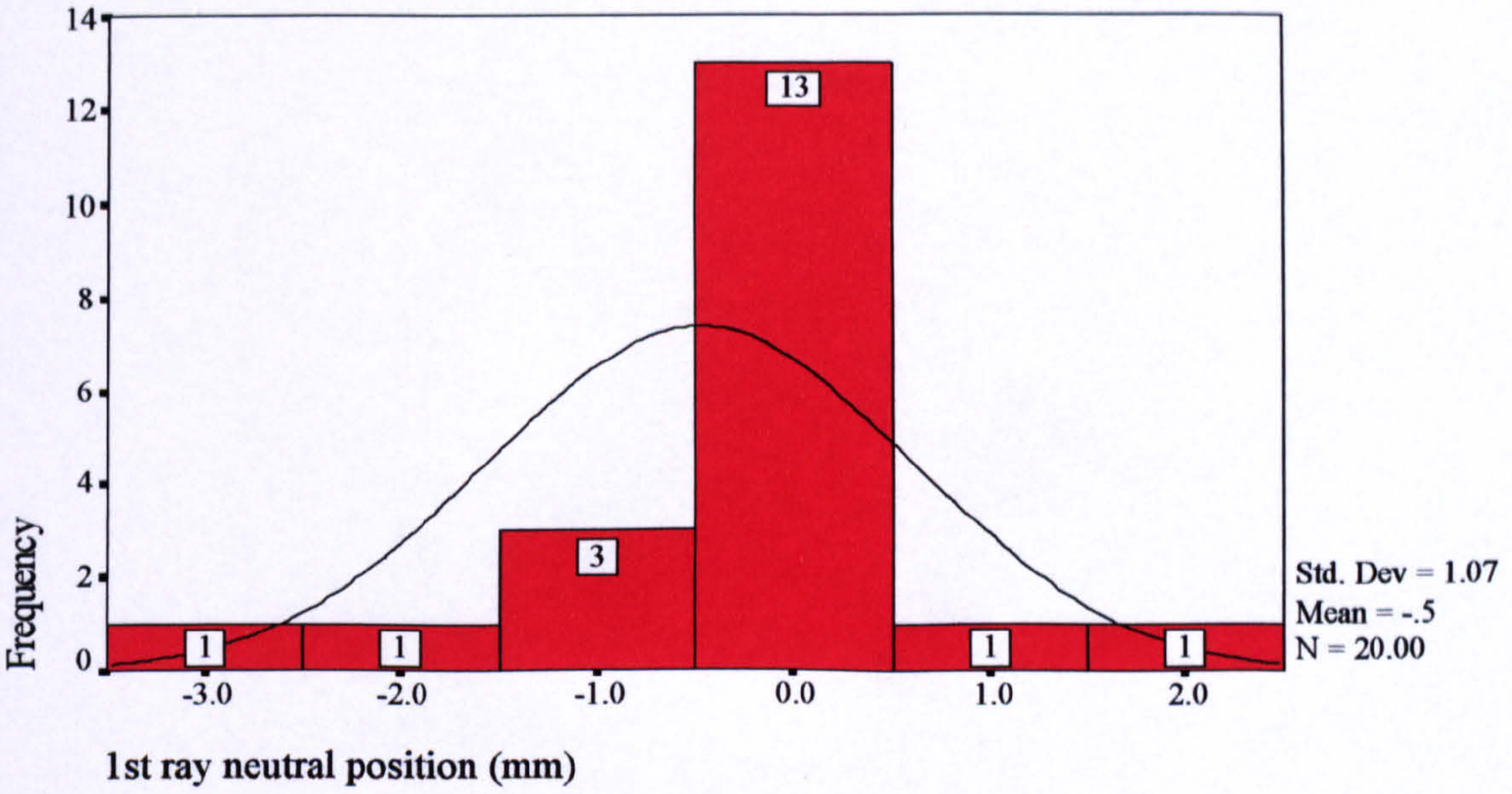


Figure 3.17: Distribution of 1st ray neutral position data right foot second measurements

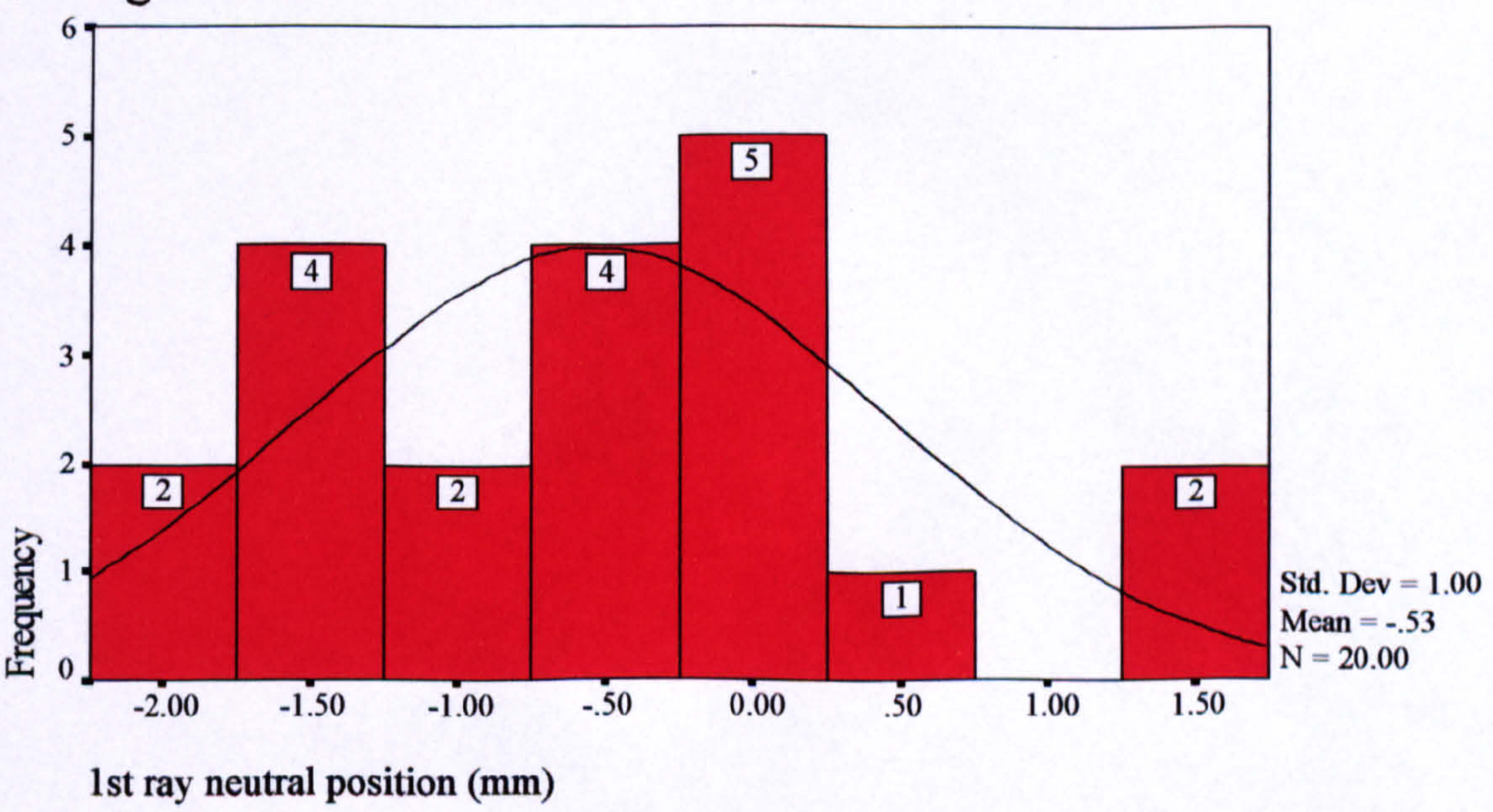


Figure 3.18: Distribution of metatarsal formula score data left foot initial measurements

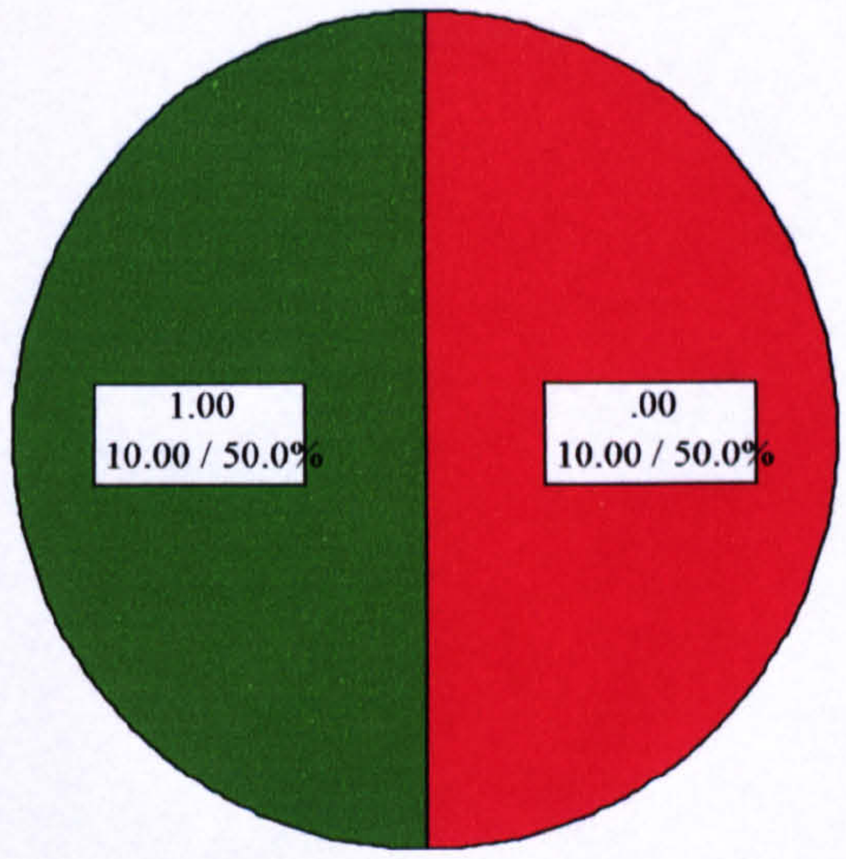


Figure 3.19: Distribution of metatarsal formula score data right foot initial measurements

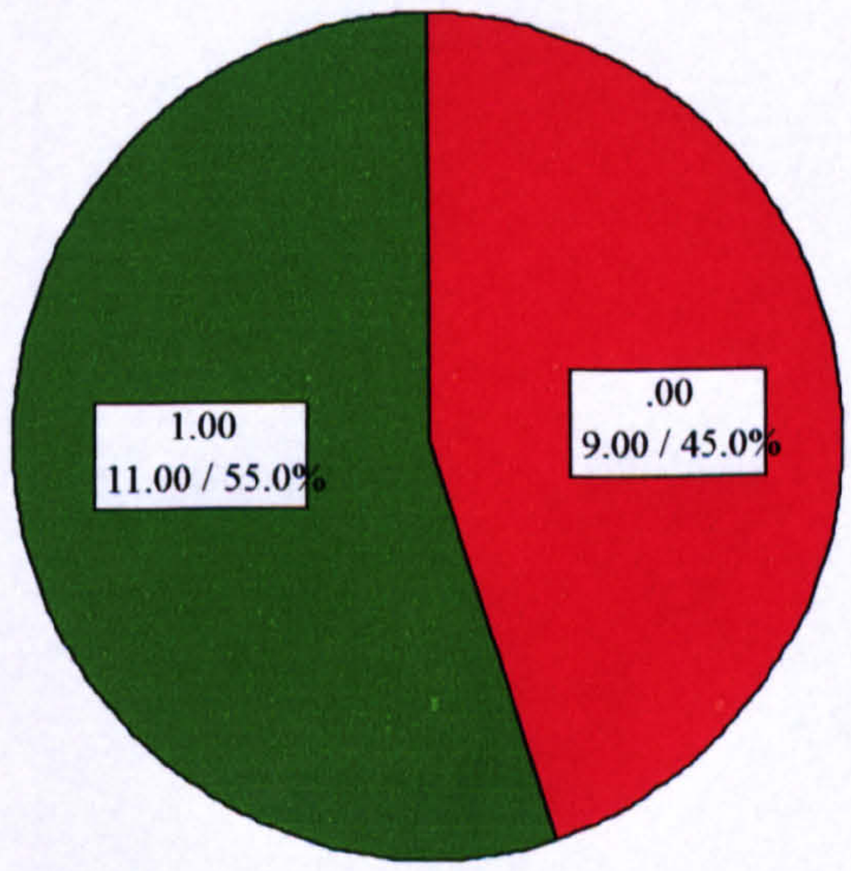


Figure 3.20: Distribution of metatarsal formula score data left foot second measurements

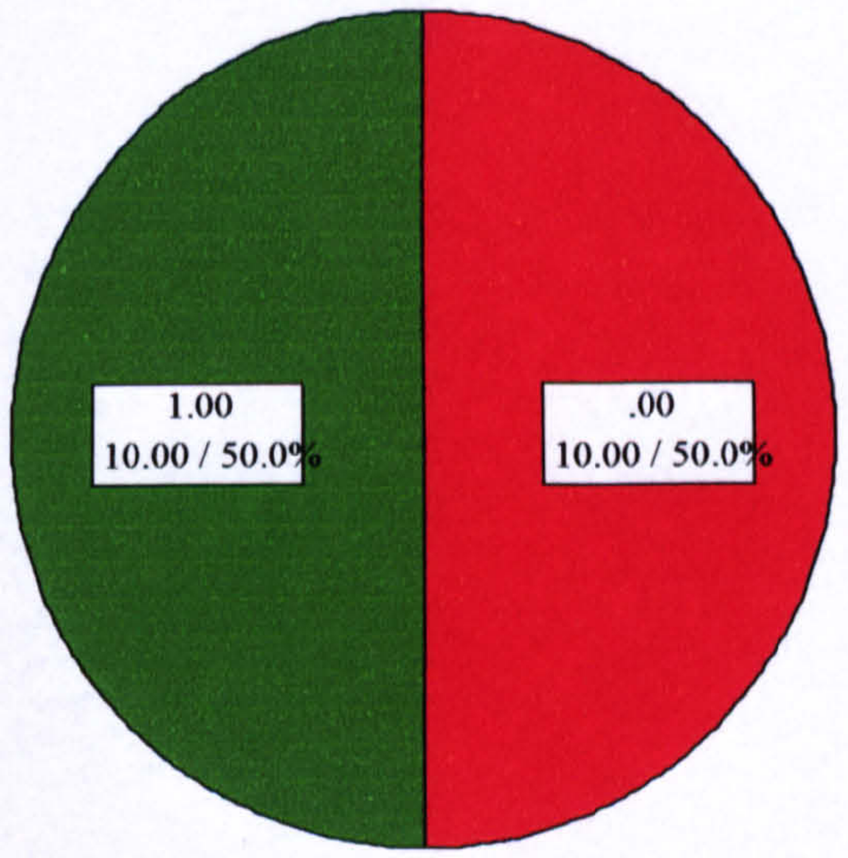


Figure 3.21: Distribution of metatarsal formula score data right foot second measurements

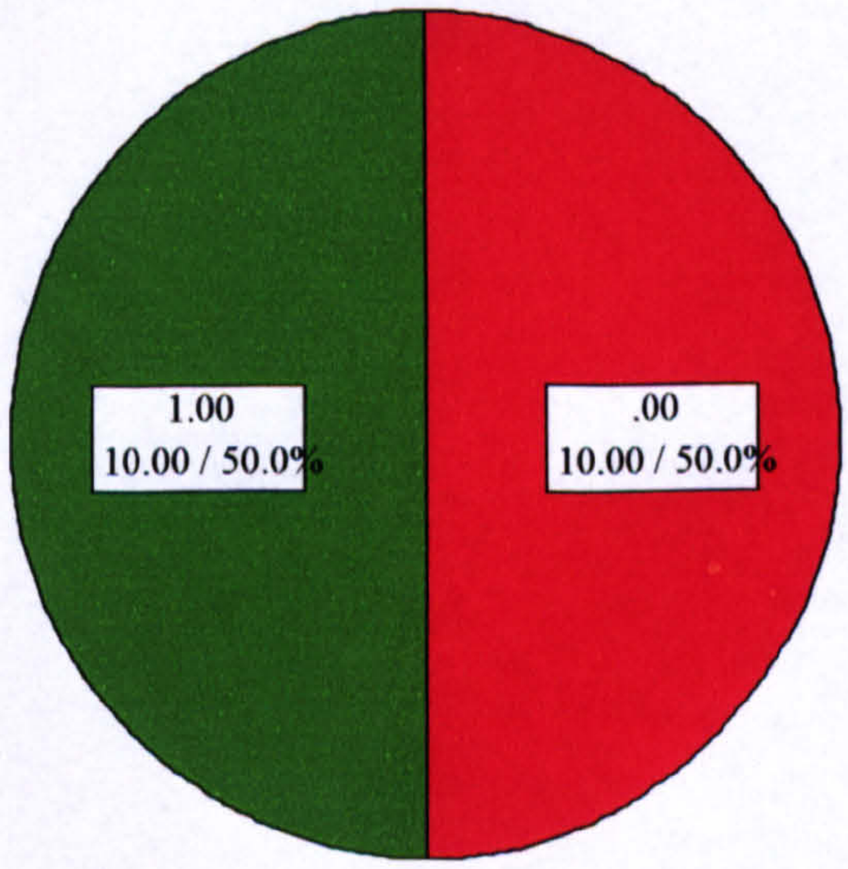


Figure 3.22: Distribution of digital formula score data left foot initial measurements

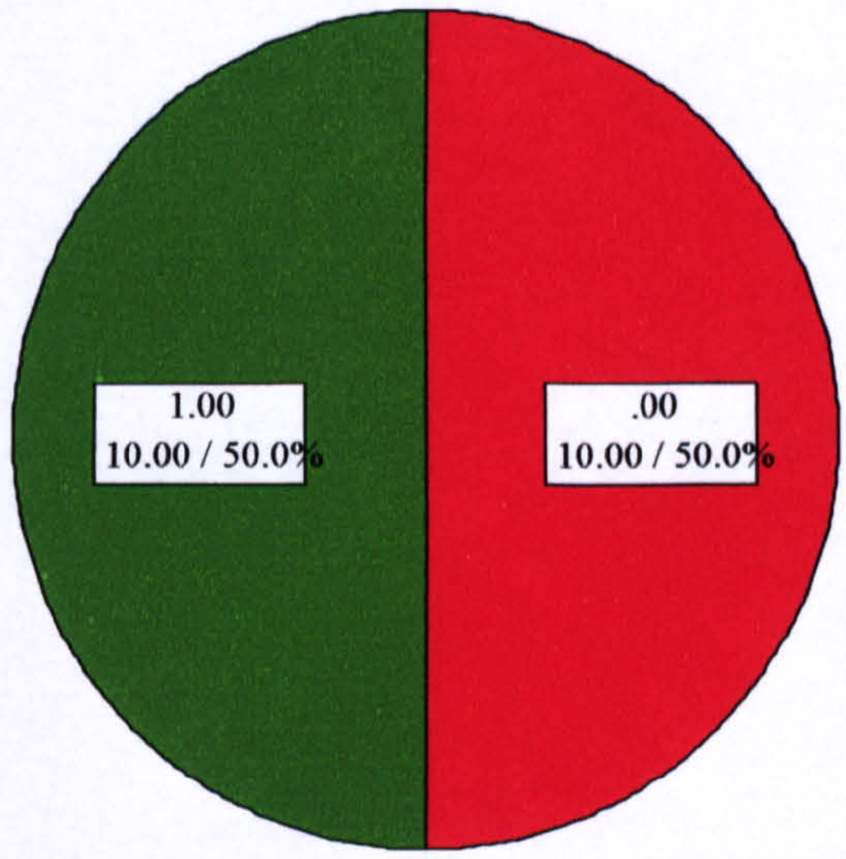


Figure 3.23: Distribution of digital formula score data right foot initial measurements

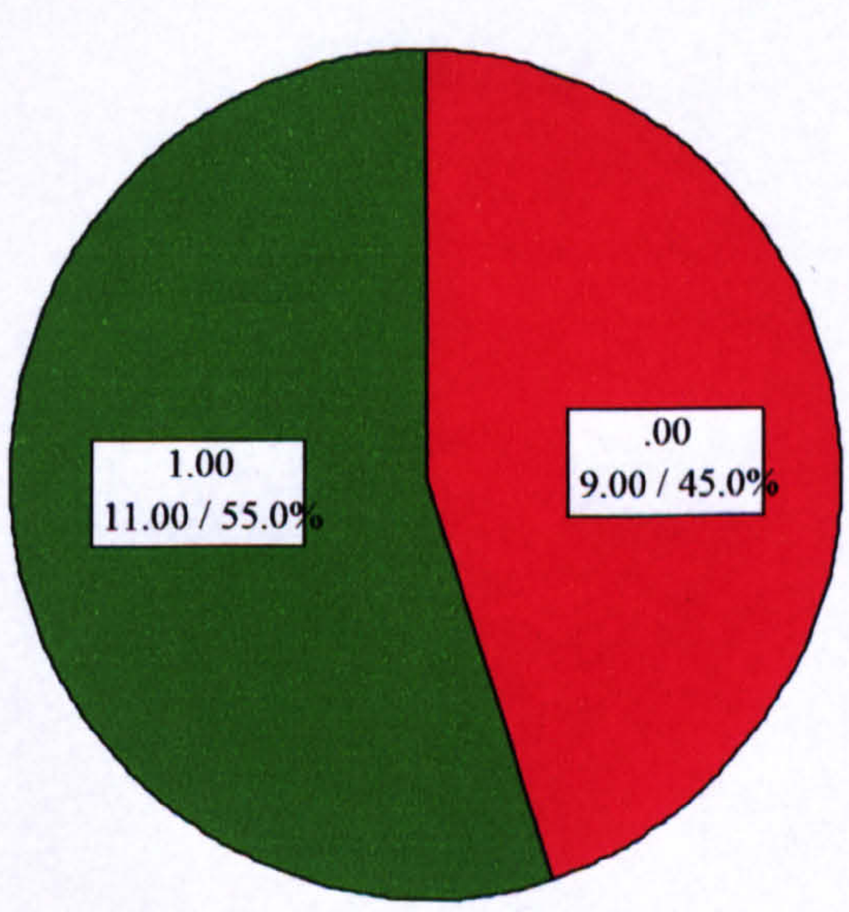


Figure 3.24: Distribution of digital formula score data left foot second measurements

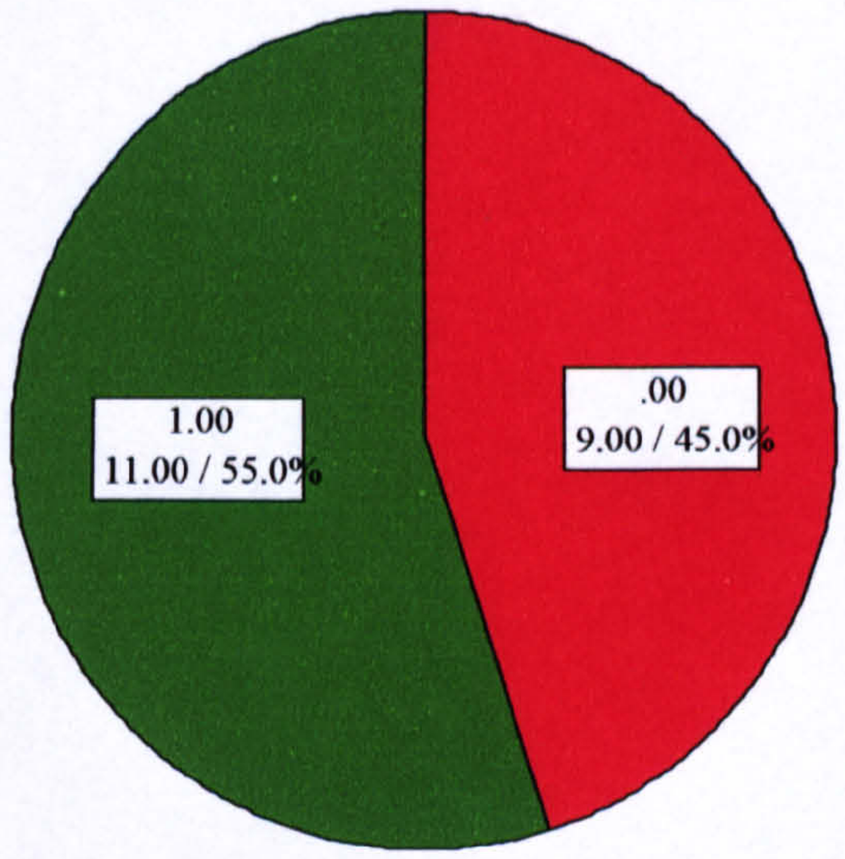
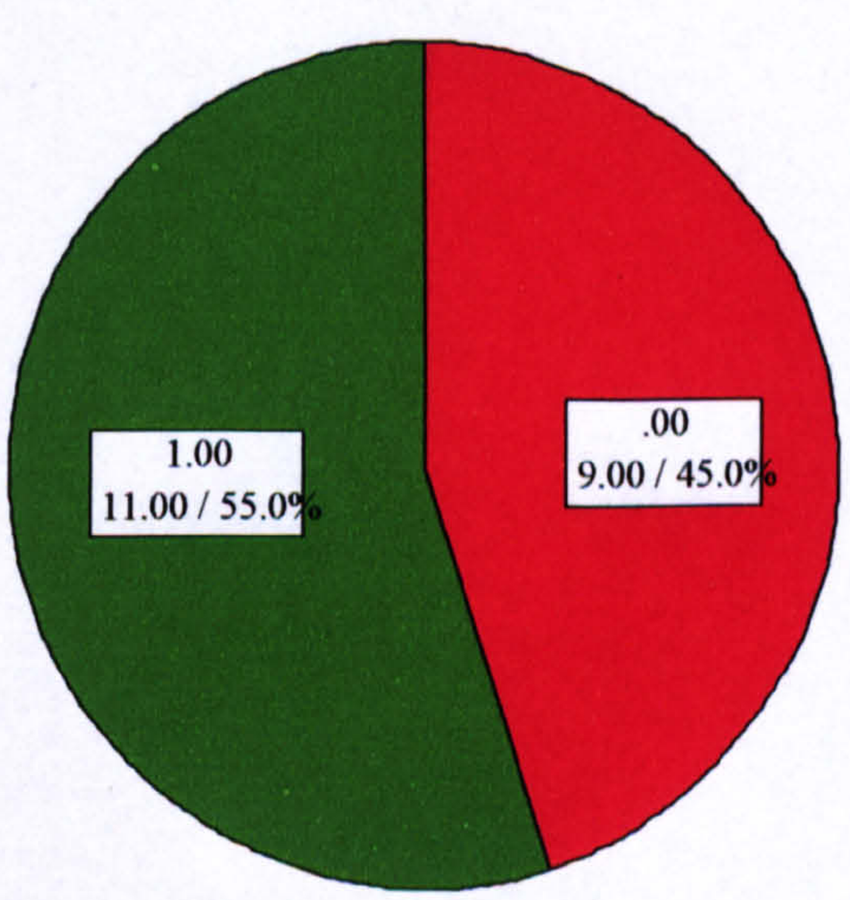


Figure 3.25: Distribution of digital formula score data right foot second measurements



Before between-day intra-observer error analysis was performed, data was examined for statistical differences between right and left feet to reveal whether pooling of right and left foot data was appropriate. If left and right foot data could be shown to be drawn from the same population then the data could be pooled, thereby increasing the sample size (n). This increases statistical power and improves the reliability of the inferences drawn.

Parametric data (1st MPJ angle, AHI and 1st RNP) was tested for significant statistical differences between left and right foot data using the paired t-test procedure (See section 3.6.1). The results of these tests are given in Table 3.4. Non-parametric dichotomous data (metatarsal and digital formula) were tested using the McNemar test. The results of these tests are given in Tables 3.5-3.8. A level of statistical significance was set at P=0.05 for all tests. Statistically significant differences are indicated by *:

Table 3.4: The results of the two sample paired T-test procedures; testing for differences between left and right foot parametric data.

	MEAN ± S.D. LEFT	MEAN ± S.D. RIGHT	T	DF	P
1st MPJ angle initial measurements	12.6 ± 4.260	12.3 ± 3.743	0.59	19	0.562
1st MPJ angle secondary measurements	12.4 ± 4.430	12.4 ± 3.817	0.00	19	1.000
AHI initial measurements	0.5590 ± 0.131	0.5655 ± 0.141	-0.62	19	0.542
AHI secondary measurements	0.5640 ± 0.137	0.5660 ± 0.133	-0.22	19	0.825
1st RNP initial measurements	-0.4500 ± 0.872	-0.5250 ± 0.786	0.37	19	0.716
1st RNP secondary measurements	-0.4750 ± 1.070	-0.5350 ± 1.002	0.52	19	0.606

Table 3.5: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between left and right foot metatarsal formula dichotomous score, initial measurements.

		Metatarsal formula dichotomous score Right foot	
		0	1
Metatarsal formula Dichotomous score	0	9	1
Left foot	1	0	10
		n=20	(Binomial) 2-tailed P = 1.0000

Table 3.6: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between left and right foot metatarsal formula dichotomous score, secondary measurements.

		Metatarsal formula dichotomous score Right foot	
		0	1
Metatarsal formula Dichotomous score	0	10	0
Left foot	1	0	10
		n=20	(Binomial) 2-tailed P = 1.0000

Table 3.7: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between left and right foot digital formula dichotomous score, initial measurements.

		Digital formula dichotomous score Right foot 0	1
Digital formula Dichotomous score	0	9	1
Left foot	1	0	10
		n=20	(Binomial) 2-tailed P = 1.0000

Table 3.8: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between left and right foot digital formula dichotomous score, secondary measurements.

		Metatarsal formula dichotomous score Right foot 0	1
Metatarsal formula Dichotomous score	0	9	0
Left foot	1	0	11
		n=20	(Binomial) 2-tailed P = 1.0000

The significance levels obtained in all tests exceeded the level set for statistical significance. No significant statistical differences existed between left and right foot measurements in any variable. Therefore, left and right foot data for all measurement variables was shown to be drawn from the same population and could be pooled, increasing the sample size (n), the statistical power, and the reliability of the inferences drawn in the examination of between-day differences. The pooled data were examined for statistical differences between initial and secondary measurements.

Parametric data were again tested using the two sample paired t-test procedure and non-parametric data were tested using the McNemar test. A level of significance was set at P= 0.05 for all tests. Table 3.9 summarises the parametric data results. Tables 3.10-3.11 summarise the non-parametric data results. Statistically significant differences are indicated by *.

Table 3.9: The results of the two sample paired T-test procedures; testing for differences between initial and secondary measurements. Parametric data.

	MEAN ± S.D. INITIAL MEASUREMENT	MEAN ± S.D. SECONDARY MEASUREMENT	T	DF	P
1st MPJ angle	12.45 ± 3.961	12.4 ± 4.081	0.17	39	0.864
AHI	0.5622 ± 0.134	0.5650 ± 0.133	-0.36	39	0.719
1st RNP	-0.4875 ± 0.820	-0.5050 ± 1.023	0.14	39	0.888

Table 3.10: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between initial and secondary measurements of metatarsal formula dichotomous score.

		Metatarsal formula Secondary Measurement dichotomous score	
		0	1
Metatarsal formula Dichotomous score	0	19	1
Initial Measurement	1	0	20
		n=40	(Binomial) 2-tailed P = 1.0000

Table 3.11: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between initial and secondary measurements of digital formula dichotomous score.

		Digital formula Secondary Measurement dichotomous score	
		0	1
Digital formula Dichotomous score	0	18	1
Initial Measurement	1	0	21
		n=40	(Binomial) 2-tailed P = 1.0000

3.4.3 Discussion

The significance levels obtained in all tests exceeded the level set for statistical significance. No statistically significant differences were identified between initial and secondary measurements in any of the foot measurements. Thus, all of the measurement techniques proved to be repeatable. It may therefore be concluded that the measurement techniques are repeatable devices that may be applied in the clinical environment with acceptable results and their use within this study is justified.

It should be noted that these results relate only to the author's ability to produce repeatable measures. The author was highly practised at the measurement techniques. This is likely to have bearing on the results obtained. Freeman (1991) demonstrated the beneficial effects of observer experience in the measurement of foot parameters. Generalisation of the results to all observers should be avoided.

3.5 Sampling Considerations and Generation of the Sample.

Before specific parameter values could be assigned to the model presented in Section 3.2 it was necessary to apply the measurement techniques described in Section 3.3 to obtain data. Clearly, a sample was required to supply this data. Before a sample was generated, consideration to the required attributes of the sample and to the sampling technique to be applied was necessary.

It was stated in Section 3.2 that the foot measurement components of the model (Equation 3.1) were partitioned into genetic and environmental components, since these factors have the potential to be determined by a combination of genetic and environmental influences and moreover, genetic inheritance and environment (footwear) are both factors proposed in their own right as significant in the actiology of hallux valgus. The relative contribution of genetic and environmental influences in the determination of the factors can be explored by the application of quantitative genetic techniques to a sample of genetically related individuals. If genetic and environmental influences on 1st MPJ angle (and thus, hallux valgus) are to be quantified, and the model refined to include this information, the study sample must consist of genetically related individuals.

Osbourne and DeGeorge (1959) maintained that: "*True random sampling is extremely difficult if not impossible to achieve, and may be quite meaningless in populations.*" They concluded that purposive sampling was rarely avoidable in the study of human inheritance using genetically related individuals. Non-probability purposive sampling relies on the underlying assumption that, with good judgement and an appropriate strategy, a sample may be generated that is satisfactory to the needs of a study. Subjects picked are judged to be typical of the population under study. The advantages of this sampling strategy are convenience and economy. The major limiting factor of this form of sampling is that it does not provide any basis for estimating how far the sample results deviate from the true population figures. While the superiority of probability sampling over non-probability sampling is acknowledged, it must be stated that this theoretical advantage is nullified if probability sampling is not carried out to the letter. Often when dealing with large samples this is not possible. Moreover, since the trait of hallux valgus was under investigation within this study, it was necessary directly to seek out individuals exhibiting this trait. This would not have been possible using probability sampling. Indeed, it is possible, however unlikely, that a random sample may have yielded no such individuals. Given this, purposive sampling was used to generate the sample.

Families of subjects were generated from various sources using several methods:

1. Letters were sent to patients attending the Northampton School of Podiatry requesting their participation in the study (See Appendix 1).
2. Posters advertising the study along with letters (as above) were displayed in the patient waiting-room at the Northampton School of Podiatry.
3. Details of the study and a request for subjects was put out over local radio and published in a local newspaper.
4. Leaflets were distributed in staff pigeon-holes at Nene College of Higher Education.
5. Individuals were directly asked to participate in the study by the author.

Once individuals had been identified as willing to participate in the study, as many members of their family as possible were contacted and enrolled within the study as subjects. Clearly, not all family members could, or wished to take part in the study. Thus, incomplete ascertainment of families resulted, with all family members willing and available to participate, undergoing assessment.

To reduce bias all volunteers were accepted for participation in the study except those meeting one or more of the following exclusion criteria.

3.5.1 Exclusion Criteria.

For the purpose of the main study it was necessary to exclude certain individuals. Individuals were excluded from the study if they met with any one of the following exclusion criteria:

1. A history of any osseous or soft tissue surgery of the foot. This was considered an essential exclusion criterion since any foot surgery would alter the form and function of the foot, potentially distorting the true value of the variables being measured.

2. Individuals with rheumatoid arthritis or any other inflammatory joint disorder were excluded from the study, as characteristic joint subluxation at the metatarsophalangeal joints manifesting as severe hallux valgus and lesser digit deformities is frequently observed in such individuals (Klenerman 1982).

3. Individuals with neurological or connective tissue disorders were excluded from the study as distortion of true values for the measured variables was likely.

4. Individuals exhibiting excessive oedema of the leg were excluded. Since many of the methods employed in the study rely on the accurate palpation of several bony prominence, swelling associated with oedema of the lower limb may render the identification of these prominence impossible.

5. Individuals under six years of age were excluded from the study. Secondary centres of ossification of the bones of the foot and leg do not generally appear until after this age (Neale and Adams 1985). Since bony positions were to be identified in the study, errors in measurement were likely to occur.

6. Pregnant women were excluded from the study as hormonal secretion associated with pregnancy is known to soften ligaments. Thus, distortion of measurements was likely.

7. Individuals were excluded from the study if the author was unable to obtain any one, or more, of the measurements.

3.5.2 Data Collection methods

A standardised data collection procedure was carried out on both feet of each subject, in the order that is recorded. All measurements were carried out by the author. Measurements were carried out using the same measuring instruments, to avoid the introduction of error. All data was recorded on a standardised data collection sheet (See Appendix 2).

3.5.3 Subject Details

Each subject's name, age and gender were recorded on the data collection sheet. Each subject was awarded a pedigree reference number.

3.5.4 Measurement of Foot Variables

The variables were measured using the standardised procedures described in section 3.3 Results were recorded on the data collection sheet.

3.6 Statistical Analyses

This section describes the statistical techniques applied to the data in developing the clinical model from descriptive to mathematical form. A review of the concepts of heritability is presented to provide the reader with an understanding of the statistical processes of quantitative genetic analysis.

3.6.1 Two Sample Paired T-test

The two sample paired t-test procedure tests the hypothesis that, in the population, two paired parametric variables are drawn from the same population and calculates the following statistic:

(Equation 3.3)

$$t = D / (S_D / \sqrt{N})$$

Where:
D= observed difference between the means of the two samples
S_D= standard deviation of the differences of the paired observations

N = number of pairs

If the probability associated with the t-value is small (P<0.05) the hypothesis that the two population means are equal is rejected.

3.6.2 The McNemar Test for Two Related Samples

The McNemar test examines cases with different values for two dichotomous variables and tests the hypothesis that both combinations of different values are equally likely. The procedure produces a 2x2 table for each pair of variables. A chi-square statistic is computed for cases with different values for the two variables. If fewer than 25 cases have different values for the two variables, the binomial distribution is used to compute the significance levels.

3.6.3 Two Sample Unpaired T-test

To test the hypothesis that, in the population, no statistically significant differences exist in two unpaired, parametric variables the two sample unpaired t-test is applied. The following statistic is calculated:

(Equation 3.4)

$$t = X_1 - X_2 / \sqrt{(S_1^2/N_1 + S_2^2/N_2)}$$

Where:
X_1= samp
le mean of group 1
X_2 = sample mean group 2
S_1^2= variance group 1
S_2^2= variance group 2
N_1= sample size group 1
N_2= sample size group 2

If the probability associated with the t-value is small (P<0.05) the hypothesis that the two population means are equal is rejected.

3.6.4 The Mann-Whitney Test

The Mann-Whitney test tests the hypothesis that two independent samples come from populations having the same distribution. To compute the test the observations from both samples are first combined and ranked. The statistic for testing the hypothesis that the two distributions are equal is the sum of the ranks for each group.

3.6.5 Regression Analysis

Regression analysis attempts to model the relationship between two or more variables (one dependent and one or more independent variables) by providing a line which minimises all vertical positive and negative deviations of the data from a line drawn through the data and thus, best indicates the trend between the co-ordinates. The method of least squares is used to fit this line. The following equation for a straight line can be fitted to explain the relationship between two variables:

(Equation 3.5)

$Y = b_0 + b_1X$

Where:

b_0 = intercept value (constant)
b_1 = regression coefficient (slope)
X = value of an independent variable
Y = predicted value of dependent variable

It is also possible to fit curvilinear functions to data to explain the relationship between two variables using regression techniques. Within this study, quadratic and cubic functions were applied in addition to the linear function:

(Equation 3.6)

$Y = b_0 + b_1X + b_2X^2$ (quadratic)

(Equation 3.7)

$Y = b_0 + b_1X + b_2X^2 + b_3X^3$ (cubic)

Multiple linear regression extends bivariate linear regression by incorporating multiple independent variables. Thus:

(Equation 3.8)

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots b_nX_n$$

To test the hypothesis that there is no linear relationship between X and Y- that the slope of the population regression line is 0- the following statistic is computed:

(Equation 3.9)

$$t = b_1 / S_{b1}$$

Where:
b_1 = regression coefficient
S_{b1}= standard error

To test the hypothesis that the intercept is 0 the following statistic is computed:

(Equation 3.10)

$$t = b_0 / S_{b0}$$

Where:
b_0 = intercept value
S_{b0}= standard error

The distribution of these statistics is Student's t with N-2 degrees of freedom (df).

An important part of any procedure that builds models from the data is establishing how well the model actually fits (goodness of fit). The goodness of fit of the model is provided by the coefficient of determination (r^2). If all observations fall on the regression line, $r^2 = 1$, if there is no linear relationship between the dependent and independent variables, $r^2 = 0$.

A further statistic can be computed which tests the hypothesis that there is no linear relationship between X and Y (population $r^2 = 0$) and thus tests the fit of the model. The total observed variability in the dependent variable (Y) is partitioned into two components: that which is attributable to the regression (regression) and that which is not (residual). The sum of squares for these values is calculated and the mean square obtained by dividing each by the degrees of freedom (df). If the regression assumptions are met, the ratio of the mean square regression to the mean square residual is distributed as an F statistic with p and N-p-1 degrees of freedom. If the probability associated with the F statistic is small the hypothesis that the population $r^2 = 0$ is rejected.

3.6.6 Heritability

The model in Section 3.2 (Equation 3.2) is multifactorial in nature. It contains several foot measurement components, each potentially influenced by the interaction of genes and the environment. To investigate the contribution of genetic and environmental influences in hallux valgus quantification of the environmental and genetic influences on the 1st MPJ angle and the foot measurement factors must be performed. Heritability is measured to achieve this. This section reviews the concepts and calculation of heritability.

The degree of lateral deviation of the hallux at the 1st MPJ is used to define hallux valgus (a 1st MPJ angle≥15° is considered to be abnormal and thus, hallux valgus; a 1st MPJ angle <15° is considered to be within normal limits). Measurements of this deviation in the population are assumed to display continuous variation: that is, that there is not either deviation or not, but there are degrees of deviation. Thus, 1st MPJ angle may be described as a quantitative or metric character (Falconer 1989). Indeed, all of the foot characteristics under investigation are quantitative characters. In the case of 1st MPJ angle the phenotypic value of an individual is the value observed, when the angle is measured. In the analyses of genetic traits within populations the phenotypic value is partitioned into causal components. In the model in Section 3.2 the phenotypic value of hallux valgus, the 1st MPJ angle, was partitioned into causal components. With the exception of age and gender, these components are dependent on the interaction of genes and environment. The genetic components are the genotype values, and the environment is all of the non-genetic circumstances. Falconer (1989) states that the interaction between genotype and environment may be considered as additive, thus the model may be simplified thus:

(Equation 3.11)

$$P = (G + E), S, A$$

Where:

P = phenotypic value (1st MPJ angle)

G = genotypic values

E = environmental deviations

S = gender

A = age

The relative proportion of the components G and E determines the genetic properties of the population, specifically, the resemblance between relatives (Falconer 1989).

Metric characters are studied as variation, genetically. The amount of variation in the character is measured in the population and expressed as the variance. For a normally distributed sample, the best estimate of the population variance is computed by:

(Equation 3.12)

$$V = \Sigma (x - X)^2 / n-1$$

Where:
x = value of the parameter for each individual
X= mean value of the parameter for the sample
n= number in sample

As before in equation 3.1, the variance can be partitioned into components. Thus:

(Equation 3.13)

$$(V1st\ MPJ\ angle_{VG} + V1st\ MPJ\ angle_{VE}) = \int (VAP_{VG}+VAP_{VE}) , (VMP_{VE}+VMP_{VE}) , (VDP_{VG}+VDP_{VE}) ,$$

$$(VPRNP_{VG}+ VPRNP_{VE}) , (VO_{VG}+ VO_{VE}) , VS, VA$$

Where:
$_{VG}$= Genotype variance
$_{VE}$= Environment (all non-genetic factors) variance
VAP= Abnormal pronation variance
VMP =1st metatarsal protrusion variance
VDP=1st digit protrusion variance
VPRNP =Plantarflexed first ray neutral position variance
VO= Other known and unknown factors variance
VS= Gender variance
VA= Age variance

or simply:

(Equation 3.14)

$$V_P = (V_G + V_E) , VS, VA$$

Where:
V_P = Phenotypic variance
V_G = Genotypic variance
V_E = Environmental variance
VS = Gender variance
VA = Age variance

The partitioning of variance allows estimation of the importance of the components, specifically, the relative importance of genetic and environmental components. The relative importance of a variation source is the variance due to that source expressed as a proportion of the total phenotypic variance. The relative importance of genetic factors (V_G) in determining phenotypic values is defined as the broad sense heritability of the character (Falconer 1989). Therefore, the proportion of the total variance caused by the effects of genes is expressed by broad sense heritability. Thus:

(Equation 3.15)

$$\text{heritability} = V_G / V_P$$

However, partitioning phenotypic variance into genetic and environmental components does not reveal the cause of resemblance between relatives. Thus, a further partition of genotypic variance is required into additive (A), dominance (D) and interactive components (I). Thus:

(Equation 3.16)

$$V_G = V_A + V_D + V_I$$

The additive variance is key, since it is the principle cause of resemblance between relatives and is, therefore, the principle determinant of the genetic properties of the population. Moreover, it is the only component that can easily be estimated from measurements made on the sample population. Thus, the important partition is into additive genetic variance versus the non-additive genetic and environmental variance. This partitioning gives the ratio V_A/V_P (Falconer 1989). This is the narrow sense heritability (h^2); it is the proportion of phenotypic variance due to additive genetic variance and is given by:

(Equation 3.17)

$h^2 = V_A / V_p$

Where:
h^2 = narrow sense heritability
V_A = additive genetic variance
V_p = phenotypic variance

The resemblance between relatives is a basic genetic phenomenon displayed by metric characters. The degree of resemblance between relatives may be detected from measurements made on the study population. It provides the means of estimating the amount of additive genetic variance and thus narrow sense heritability (Falconer 1989). In Equation 3.13 phenotypic variance of hallux valgus, 1st MPJ angle, was partitioned into causal components. However, the measurement of degree of resemblance between relatives requires that the phenotypic variance is partitioned into components corresponding to the grouping of individuals into families. Thus, the resemblance between related individuals can be examined either as similarities of individuals within the same family (e.g. parents and their offspring) or as differences between individuals in different families. The degree of resemblance can therefore be expressed as the between group component as a proportion of the total variance. It expresses the amount of variance that is common to members of the same group. This is termed the covariance. When resemblance between parents and their offspring are studied, observations are grouped into pairs- one parent or the mean of two parents, paired with one or the mean of several offspring. The between pair component of variance then only has meaning if the variances between parent and offspring values are equal; often this is not the case. Therefore, the covariance between offspring and parents is calculated from the sum of cross-products. The degree of resemblance is given by the regression of offspring on parents (Falconer 1989):

(Equation 3.18)

$b_{OP} = COV_{OP} / \delta_P^2$

Where:
b_{OP} = the slope of the regression line of offspring values on parent values
COV_{OP} = the covariance of offspring and parents
δ_P^2 = the variance of parents

Thus, the property of the population sought in the study of resemblance between relatives is the covariance of related individuals. The covariance is a proportion of the phenotypic variance and is composed of causal components attributable to either genetic or non-genetic factors.

Parent/offspring relationships are explored within this study. Thus the genetic covariance's sought for the variables are those between offspring and single parent, and offspring and mean (mid) parent values. Falconer (1989) demonstrates the derivation of these covariance's. Since offspring and parents have 50% of their genes in common (Cummings 1994), the covariance of offspring and one parent is half the additive genetic variance of the parent.

Thus:

(Equation 3.19)

$COV_{OP} = 0.5\ V_A$

The regression of offspring on one parent is given by dividing the covariance by the variance of the parents, which is the phenotypic variance of the population. Thus:

(Equation 3.20)

$b_{OP} = 0.5\ (V_A / V_P)$

Providing that the variances between genders is equal the covariance between offspring and mid-parent is the same as that between offspring and one parent. However, the degree of resemblance is not identical. The regression of offspring on mid parent values is given by:

(Equation 3.21)

$b_{OP} = 0.5\ V_A / 0.5\ V_P = V_A / V_P$

Thus, the regression of offspring on parents provides the means of estimating the proportionate amount of additive genetic variance, V_A / V_P or narrow sense heritability of a given trait.

Heritability is a descriptive statistic that applies to populations and therefore describes a situation involving a specified phenotype within a specified population with a certain arrangement of genetic and environmental factors at a specific time. If any of these specifications change, heritability will also change (Cummings 1993, Plomin et al. 1990).

Family studies are used to demonstrate resemblance between relatives for metric characters. If resemblance is observed, it may be due to either shared genetic or shared environmental influences. Family studies do not show whether observed familial resemblance is caused by shared environment or shared heredity. They do, however, provide an upper-limit estimate of heritability (or between family environmental influences) (Plomin et al. 1990).

CHAPTER IV

RESULTS

"Statistics is the only tool by which an opening can be cut through the formidable thicket of difficulties that bars the path of those who pursue the science of man" (Galton 1889)

4.1 Introduction.

This chapter presents the results of statistical analyses of the data collected for this study. All statistical analyses were performed using S.P.S.S. for Microsoft Windows Release 6.0. The chapter is divided into two parts: Part I (Sections 4.2- 4.) presents the genetic analyses and the estimation of heritability; Part II (Sections 4.4-4.) addresses the predictive modelling of data.

PART I

4.2 Sample

The sample generation techniques described in Section 3.5 yielded a sample of 579 individuals from 159 family groups (mean number of individuals per family = 3.64). All subjects were Caucasian. Graphical representations of the data for the sample are given in Figures 4.1-4.12.

Figure 4.1: Gender distribution of sample

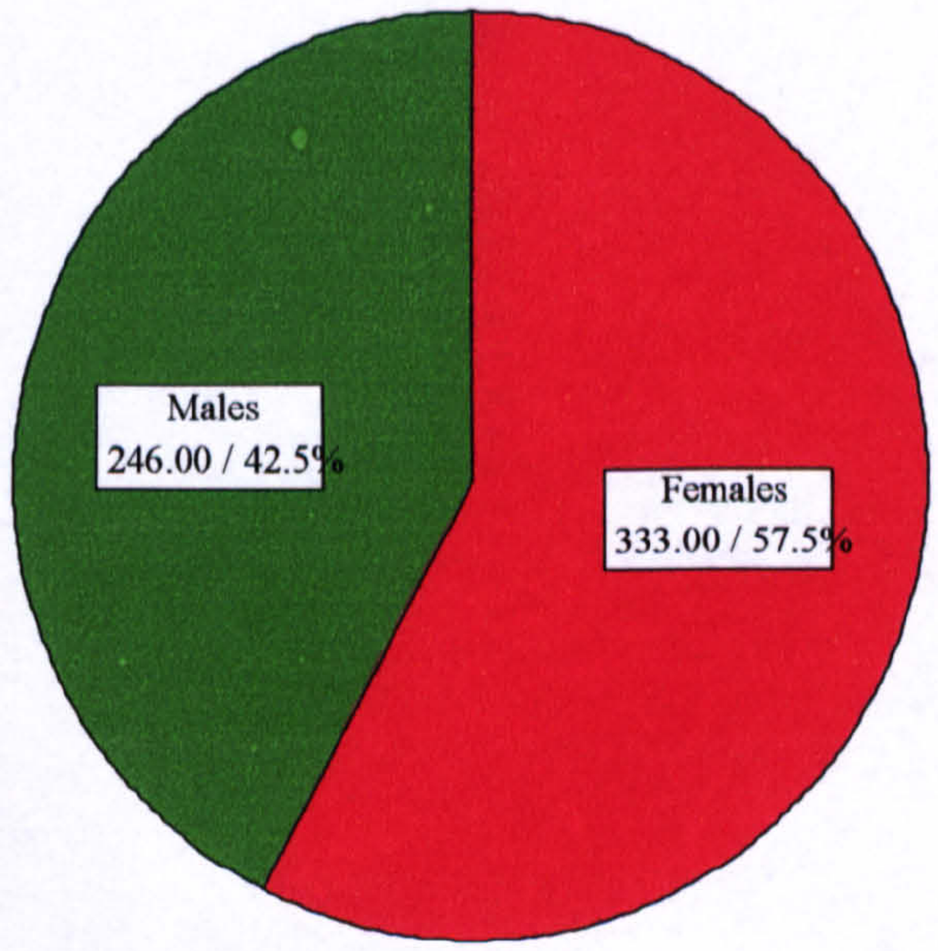


Figure 4.2: Age distribution of sample

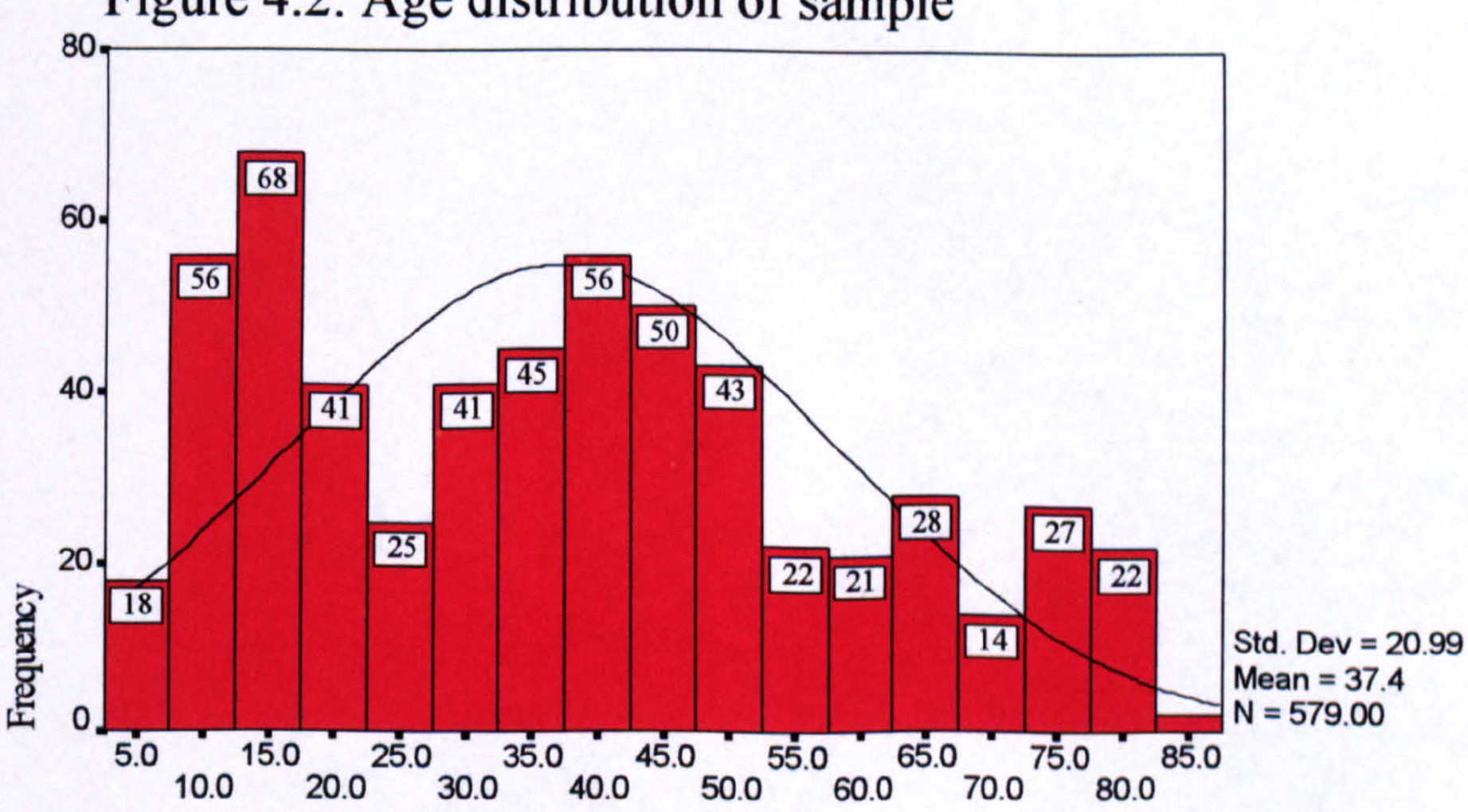


Figure 4.3: Distribution of 1st MPJ angles left foot data

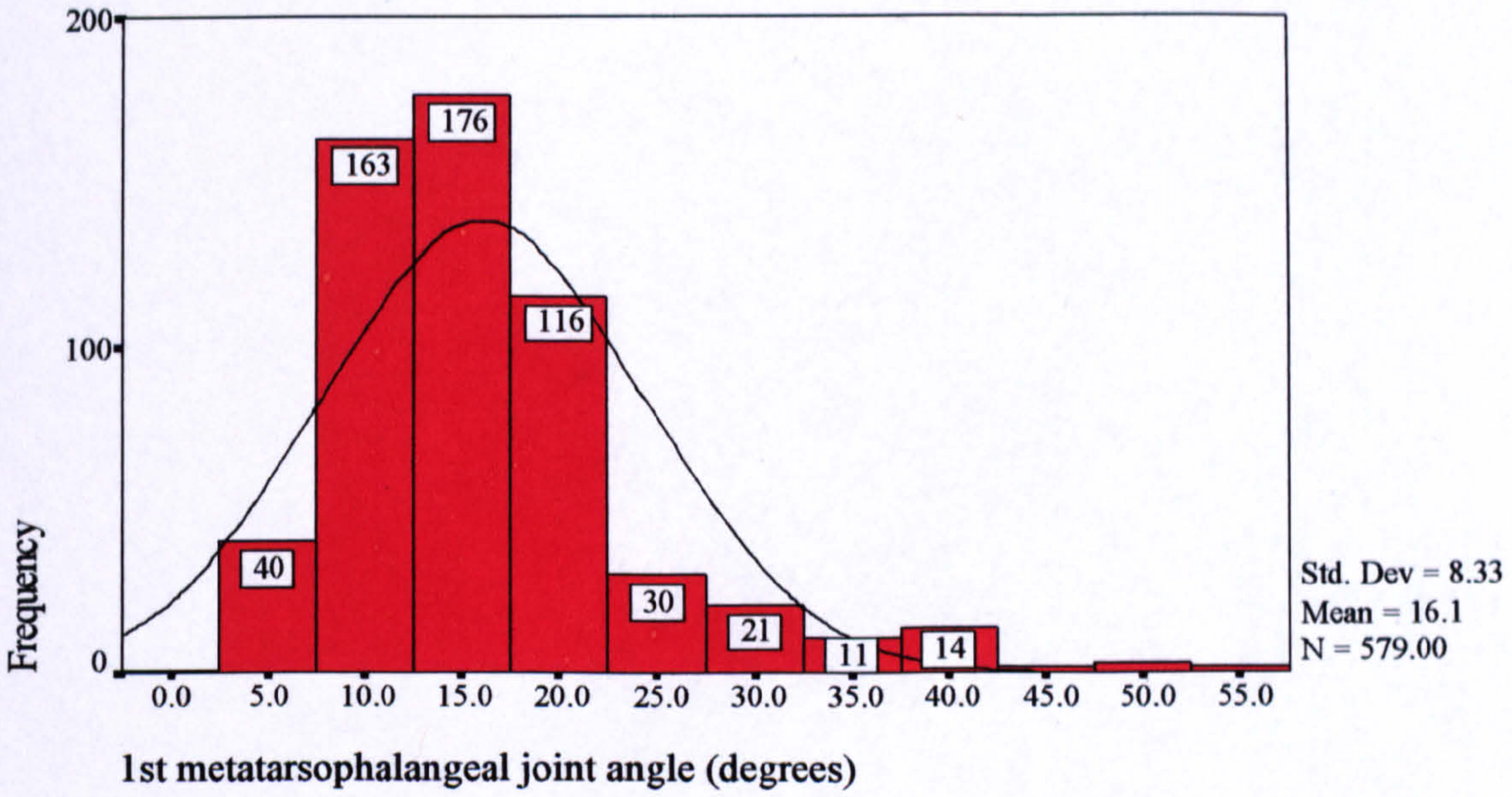


Figure 4.4: Distribution of 1st MPJ angles right foot data

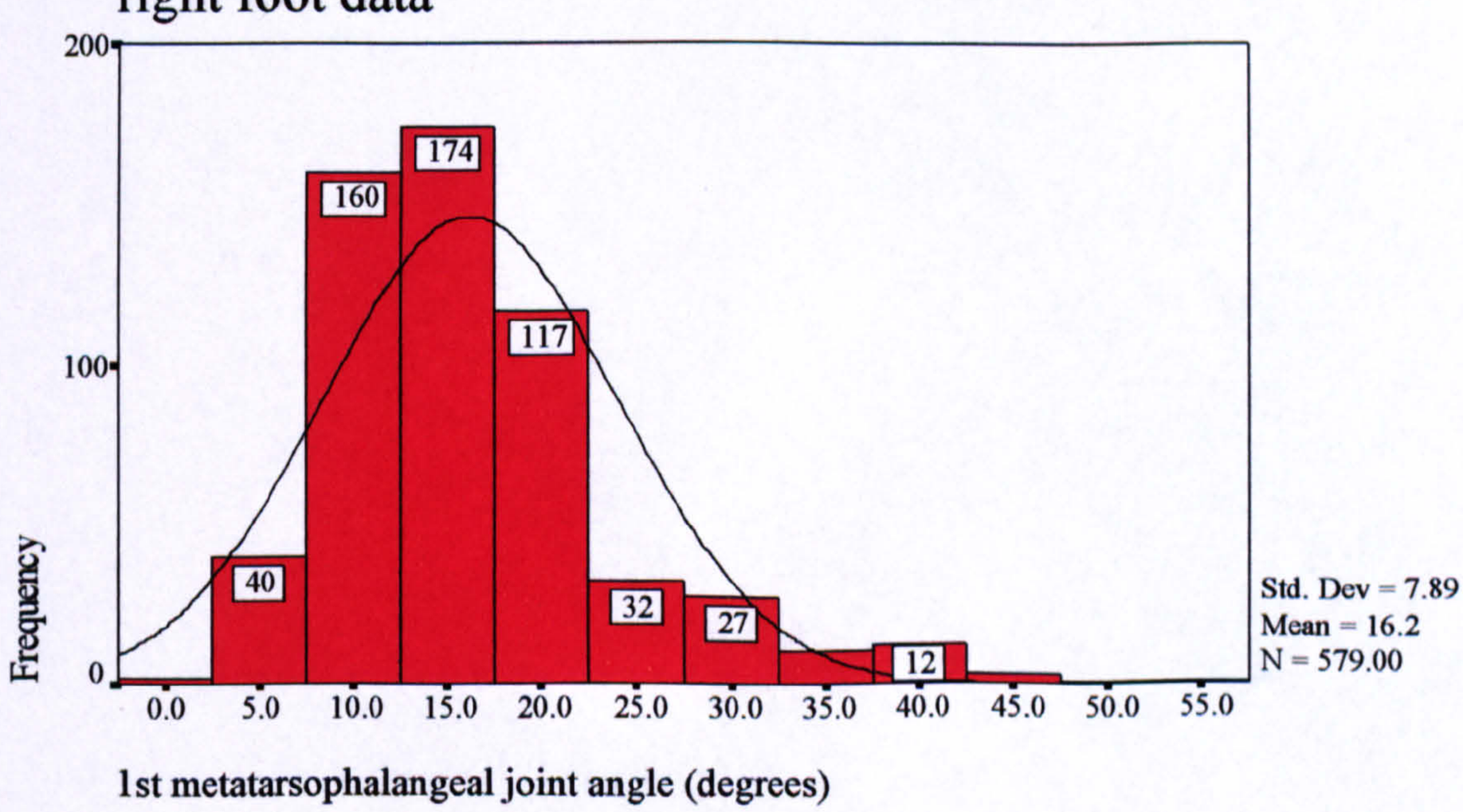


Figure 4.5: Distribution of arch height indices left foot data

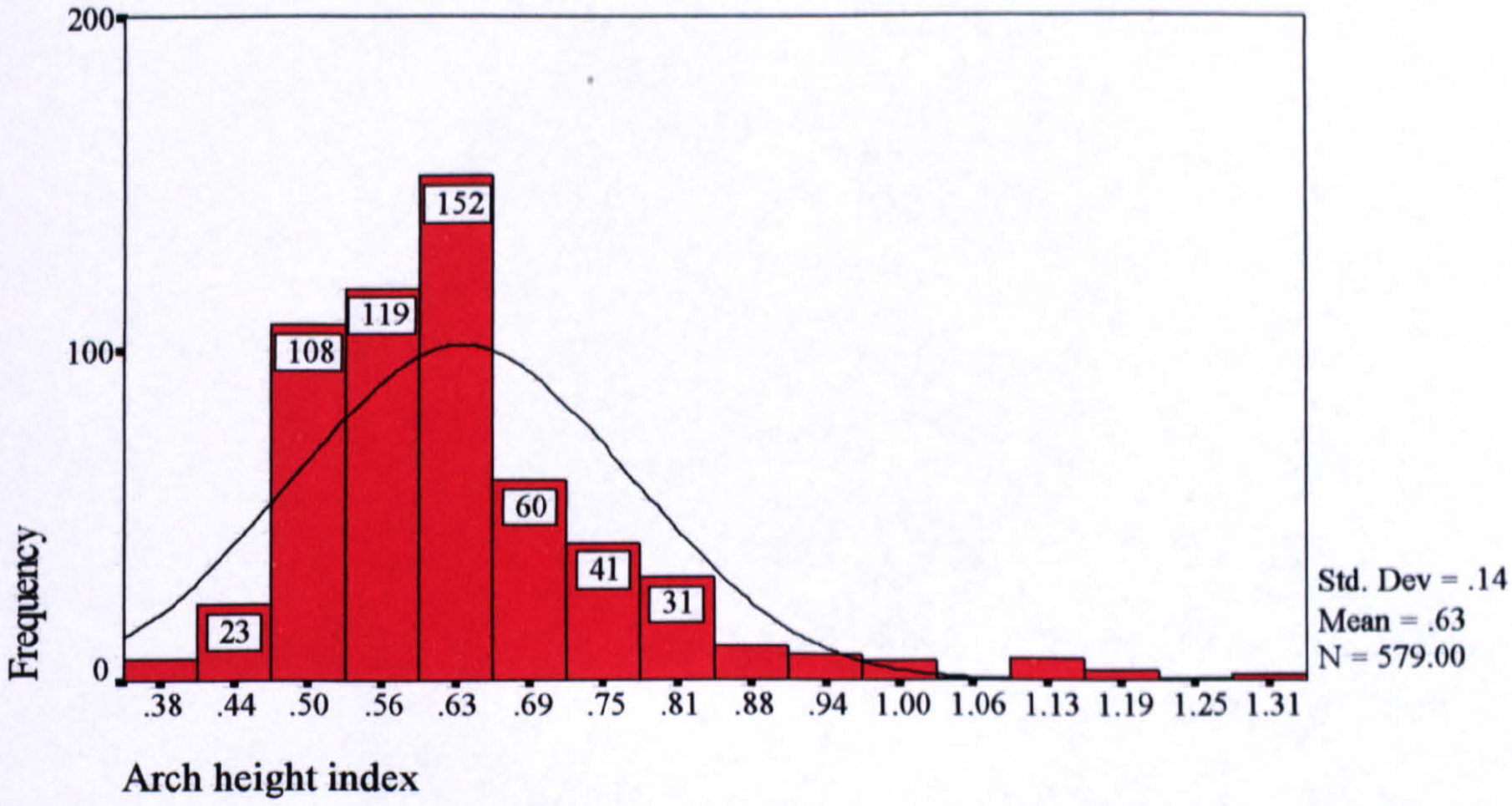


Figure 4.6: Distribution of arch height indices right foot data

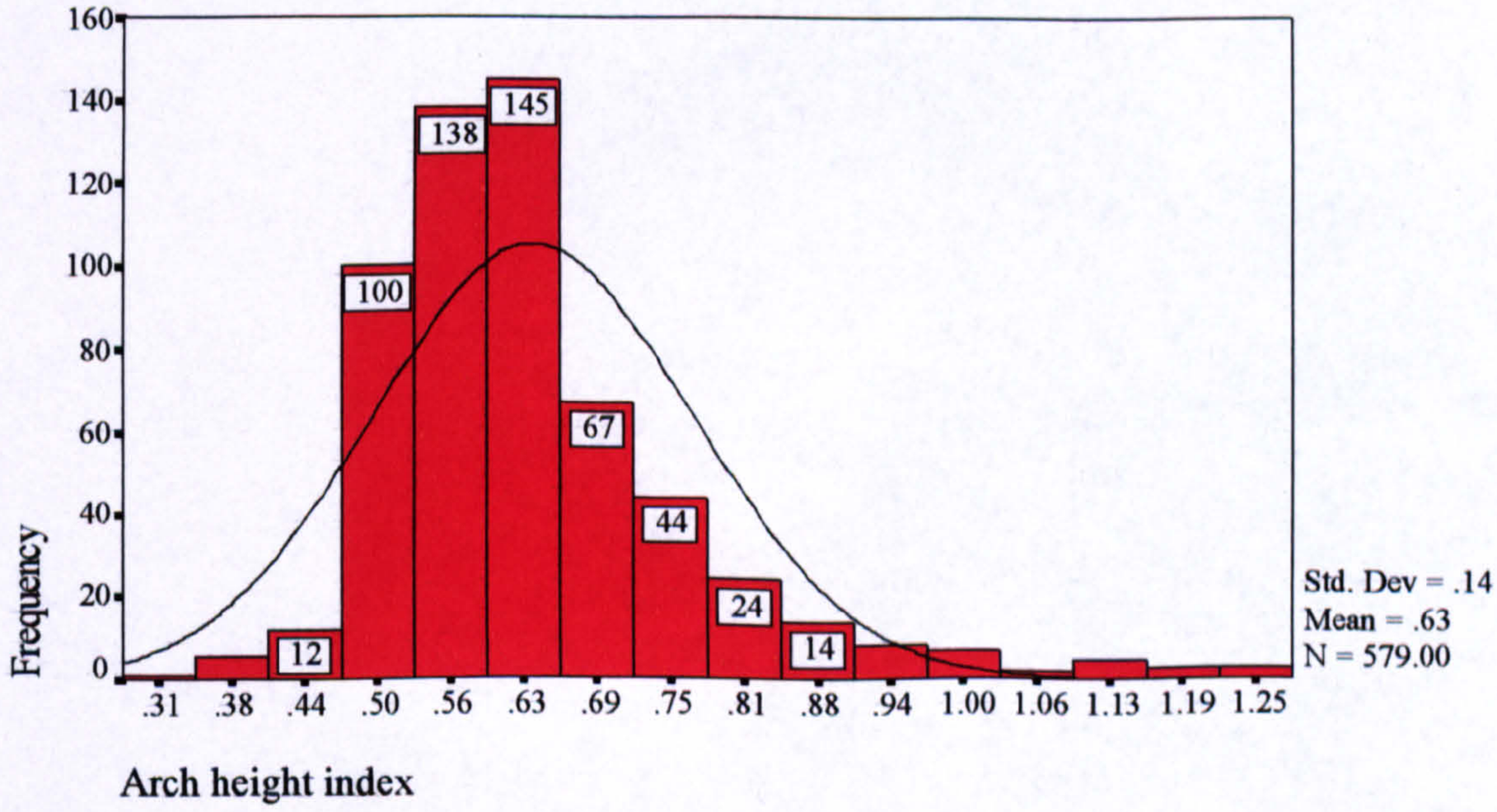


Figure 4.7: Distribution of 1st ray neutral positions left foot data

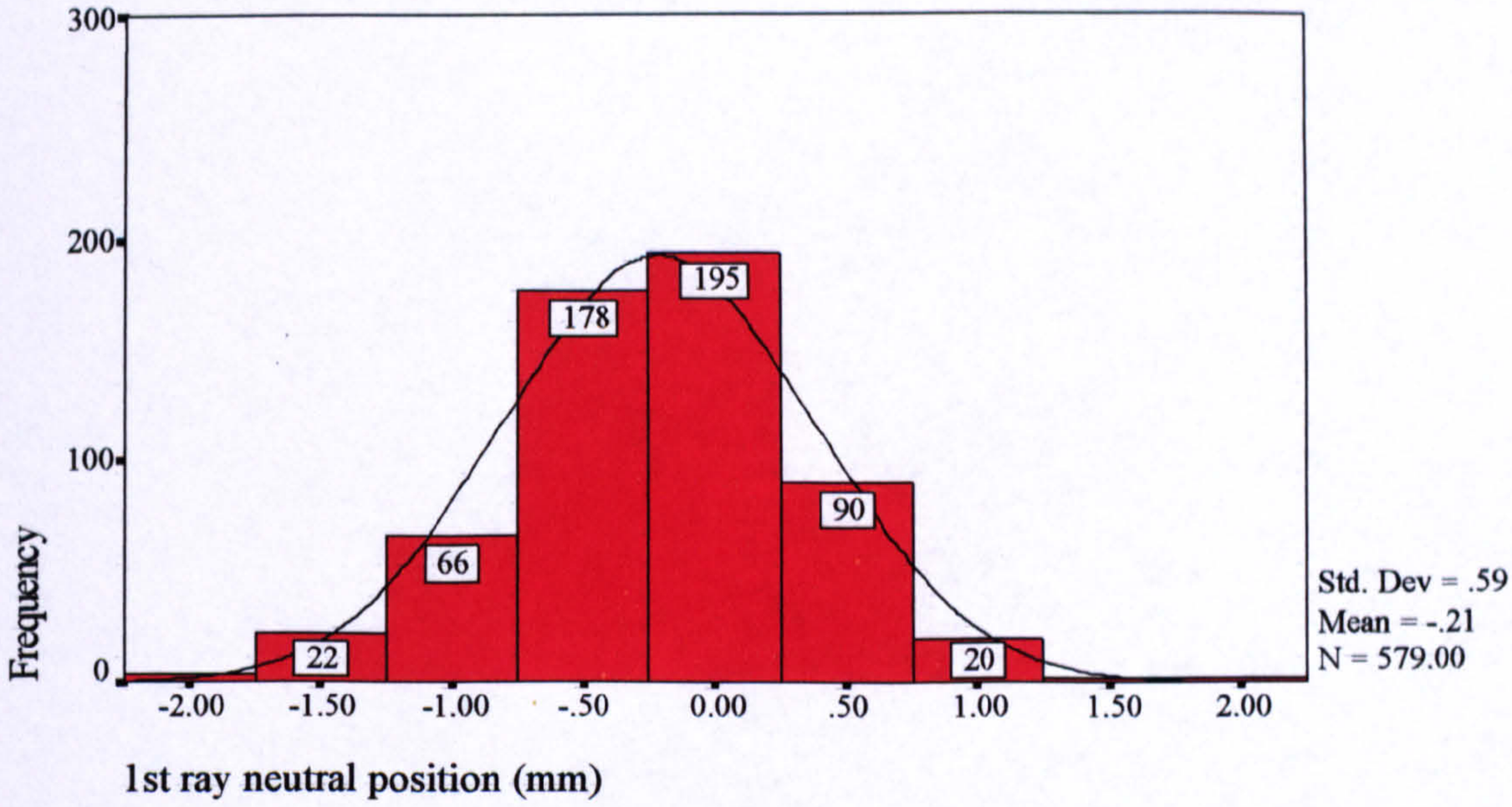


Figure 4.8: Distribution of 1st ray neutral positions right foot data

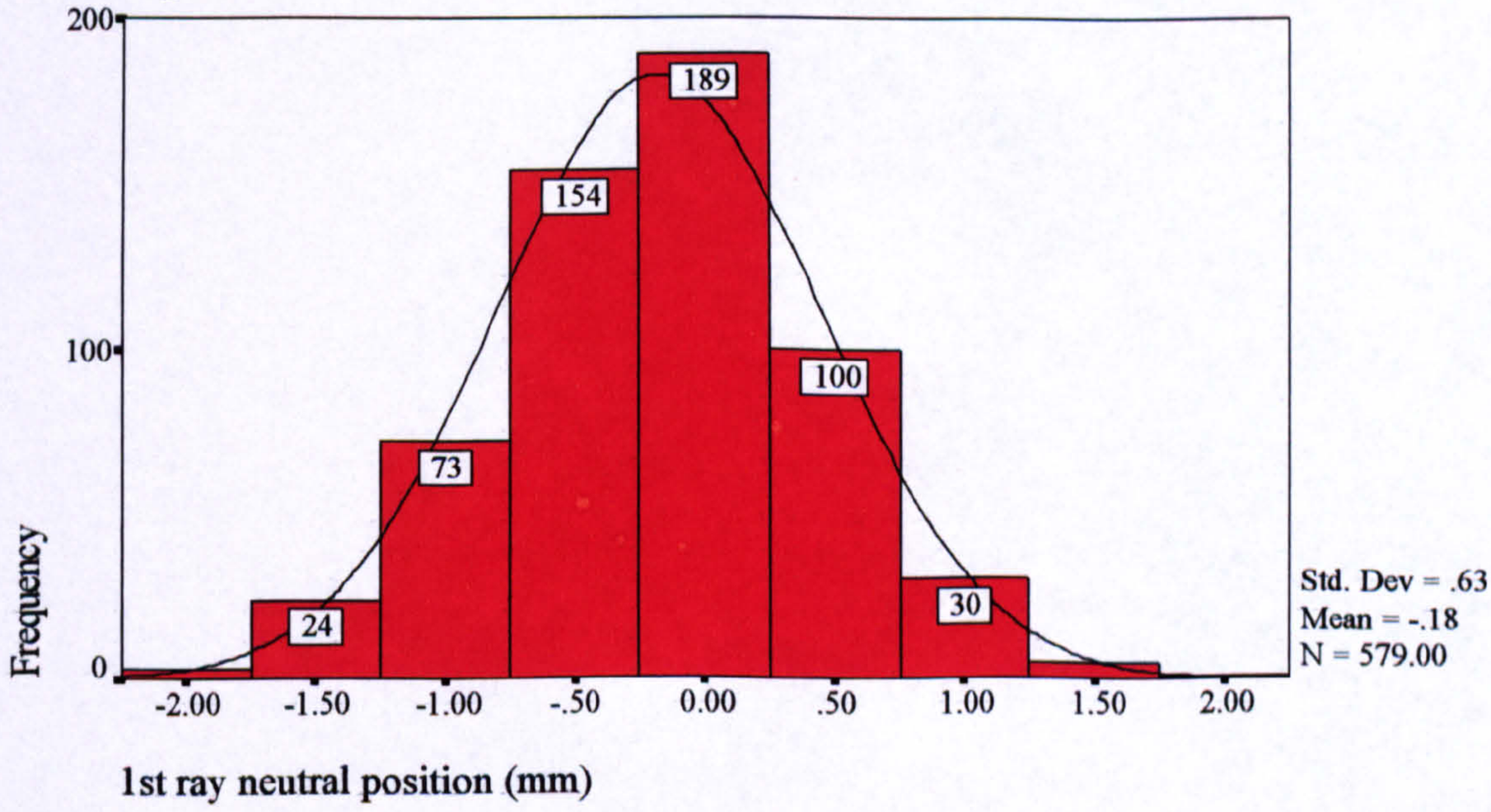


Figure 4.9: Distribution of metatarsal formula scores left foot data

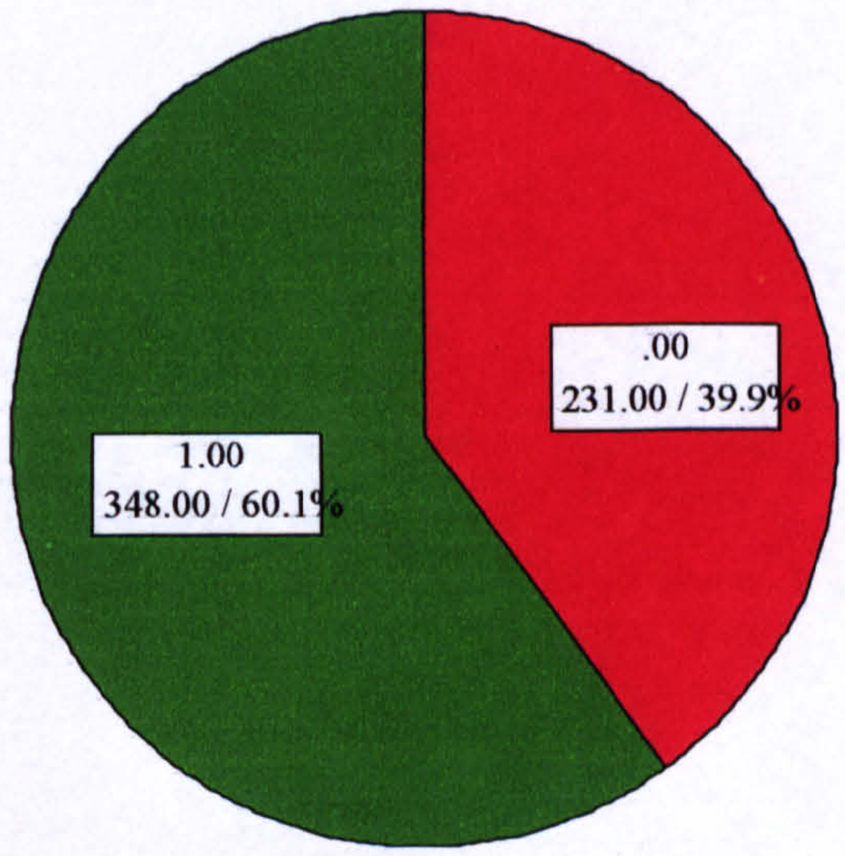


Figure 4.10: Distribution of metatarsal formula scores right foot data

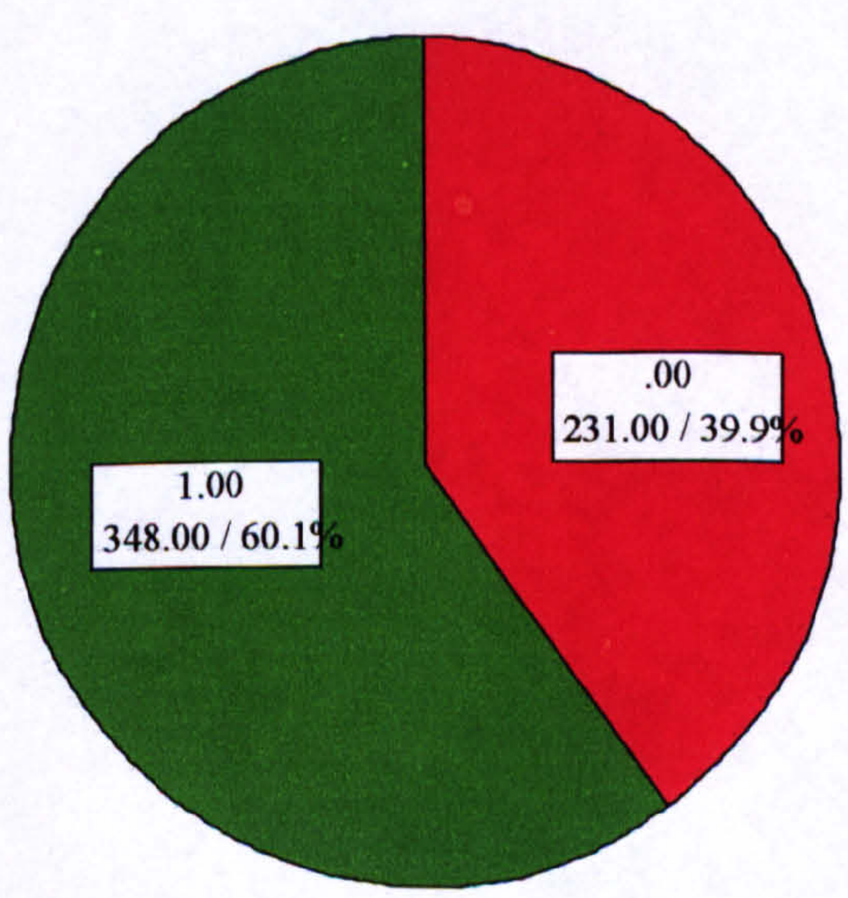


Figure 4.11: Distribution of digital formula scores left foot data

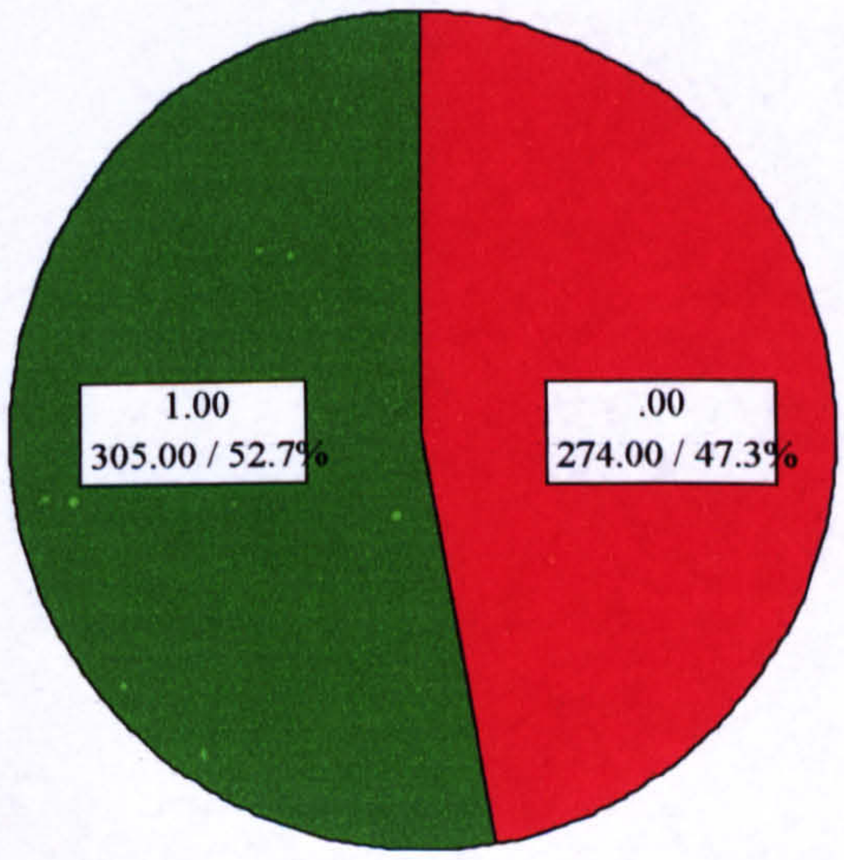
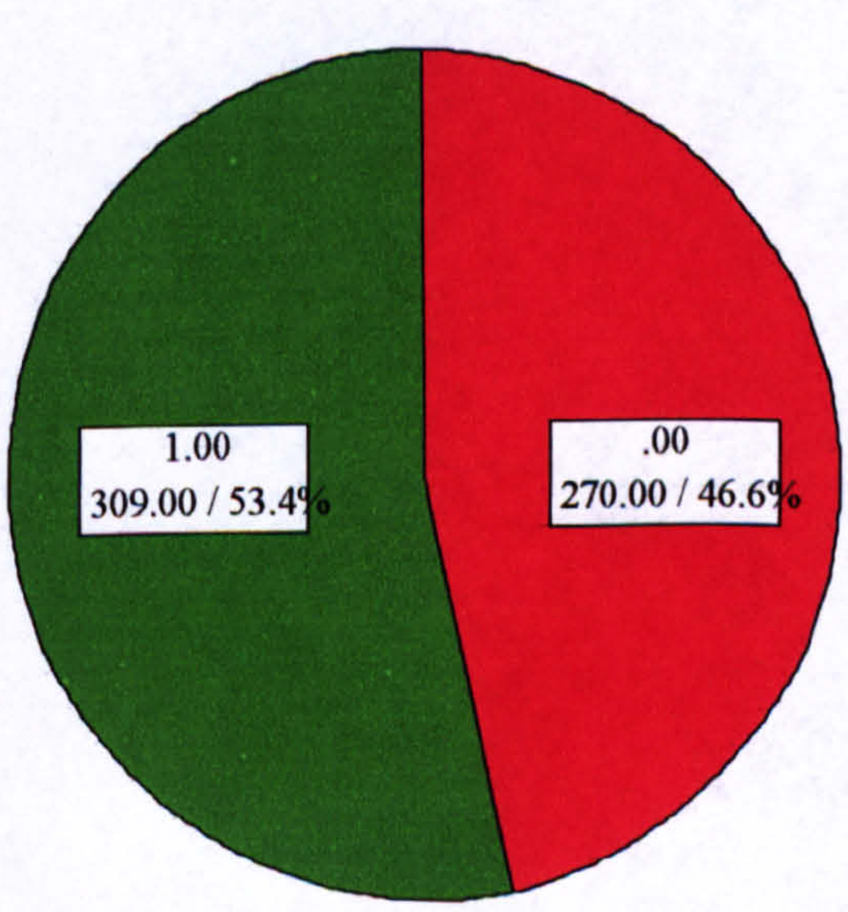


Figure 4.12: Distribution of digital formula scores right foot data



The adequacy of the sample size was tested using a retrospective power analysis. Data for left foot male and female 1st MPJ angles were used.

Cohen (1977) provides tables of power (1-β) as a function of the significance criteria (α) and the probability of detecting a clinically relevant difference (δ). For the purpose of the study α was set at 0.05. The probability of detecting a clinically relevant difference (δ) was calculated using equation 4.1:

(Equation 4.1)

$$\delta = \gamma \sqrt{(n / 2)}$$

Where:

γ = population effect size

n = sample size

The effect size (γ) is given by equation 4.2

(Equation 4.2)

$$\gamma = \mu / SD$$

Where:

μ = Minimum detectable difference in measurements

SD = Pooled standard deviation for both females and males

μ was set at 2^{O} since the goniometer used to measure 1st MPJ angle had a scale with increments of 2^{O}. Thus, this was the minimum detectable difference.

Solving Equation 4.2. for left foot female and male 1st MPJ angle data yields:

$$\gamma = 2 / 8.33 = 0.240$$

Solving Equation 4.1 yields:

$$\delta = 0.240 \sqrt{(579 / 2)} = 4.085$$

From Cohen (1977) power (1-β) was established to be 98%, at α=0.05 and δ= 4.085. The sample size of 579 individuals must therefore be considered adequate and the cessation of data collection justified.

4.3 Testing for Differences in Left and Right Foot Data

Data were examined for statistical differences between left and right feet to reveal whether pooling of right and left foot data was appropriate. If left and right foot data could be shown to be drawn from the same population then the data could be pooled, thereby effectively increasing the sample size (n). This increases statistical power, and improves the reliability of the inferences drawn.

Table 4.1 summarises the results of the two sample paired T-test procedures used to examine differences in the parametric data (1st MPJ angle, arch height index and 1st ray neutral position). The results of the McNemar procedures used to examine differences in non-parametric dichotomous data (metatarsal formula and digital formula) are presented in Tables 4.2 and 4.3. Statistically significant differences at a level of P=0.05 are indicated by *:

Table 4.1: The results of the two sample paired t-test procedure; testing for differences between right and left foot parametric data.

	Mean ± S.D. Left	Mean ± S.D. Right	t	df	P
1st MPJ angle	16.1002 ± 8.329	16.1969 ± 7.892	-.83	578	0.404
AHI	0.6305 ± 0.141	0.6326 ± 0.138	-1.20	578	0.230
1st RNP	-0.2142 ± 0.595	-0.1770 ± 0.630	-1.39	578	0.166

Table 4.2: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between right and left foot data, metatarsal formula dichotomous scores.

		Metatarsal formula right foot dichotomous score	
		0	1
Metatarsal formula dichotomous score left foot	0	231	0
	1	0	348
		n=579	(Binomial) 2-tailed P = 1.000

Table 4.3: The results of the non-parametric two-related sample McNemar test procedure; testing for differences between right and left foot data, digital formula dichotomous scores.

		Digital formula right foot dichotomous score	
		0	1
Digital formula dichotomous score	0	261	13
left foot	1	9	296
		n=579	(Binomial) 2-tailed P = .524

All significance levels obtained exceeded the level set for statistical significance (P=0.05). It may be concluded that no statistically significant differences existed between left and right foot data in any of the foot measurement variables. Thus, left and right foot data could be considered to be drawn from the same population and were pooled for the purpose of further analyses.

4.4 Examination of Gender Differences

Falconer (1989) states that regression of offspring data on mid-parent values for the estimation of heritability is inappropriate if differences exist in the variances of the data between genders. Moreover, if differences do exist in the variances of data between genders, gender adjustment of heritability estimates is necessary. Thus, examination of gender differences within the data was necessary before the heritability of the variables was estimated.

Since no statistical differences had been identified between right and left foot measurement data (Section 4.3), pooled left and right foot measurement data were examined for statistical differences between males and females. Data were divided by gender. Graphical representations of male and female data are presented in Figures 4.13-4.24.

Figure 4.13: Age distribution of males

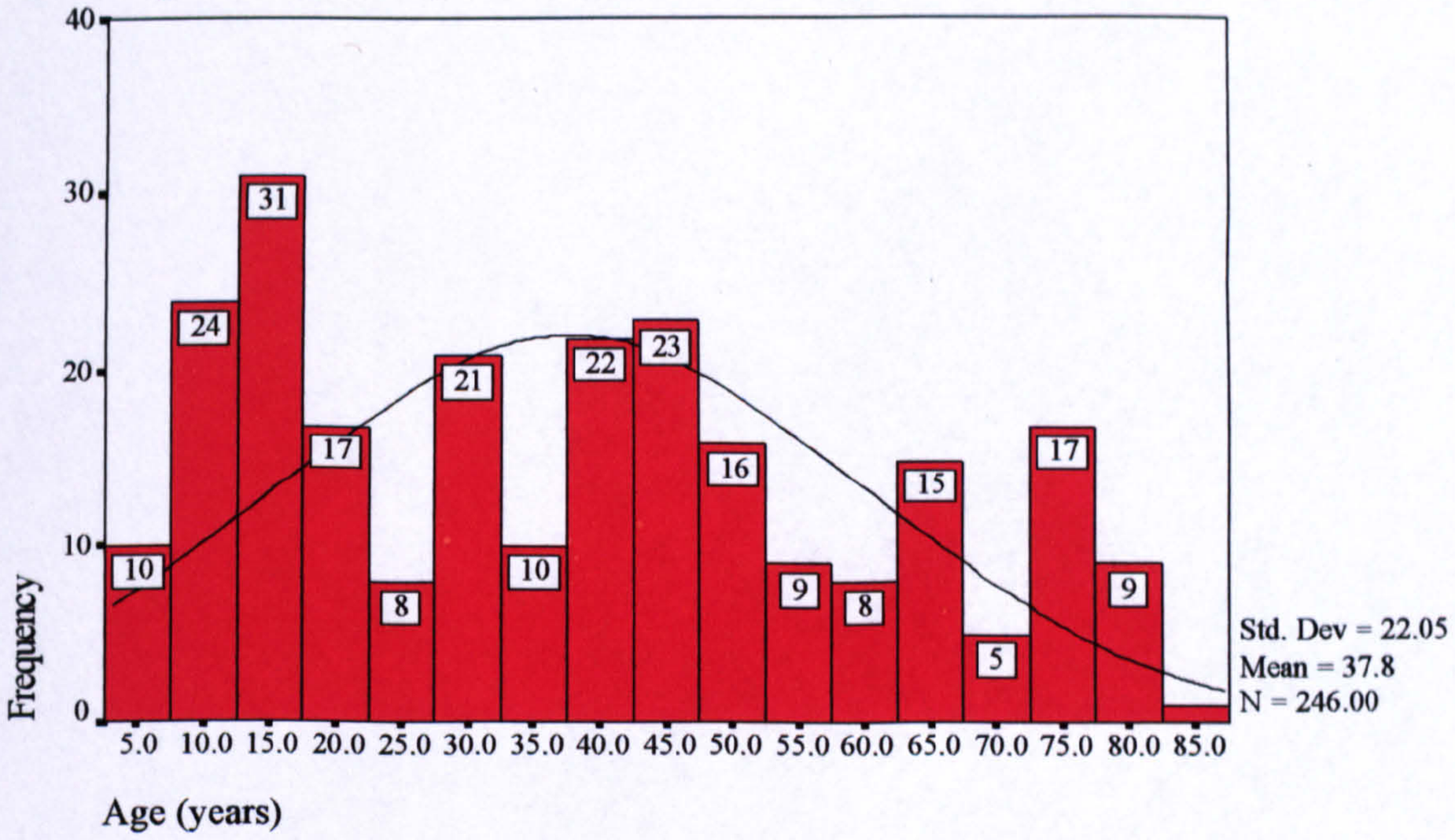


Figure 4.14: Age distribution of females

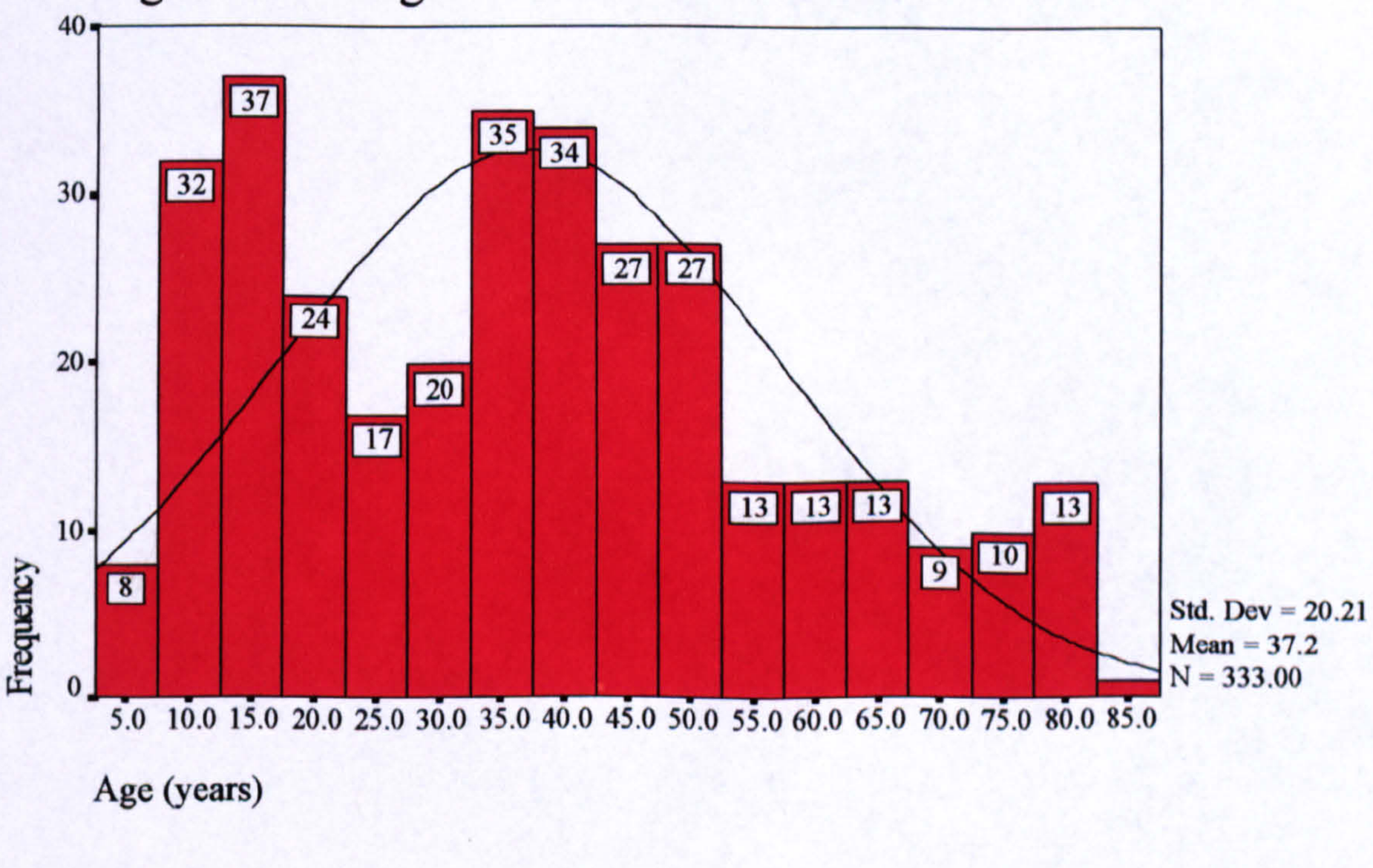


Figure 4.15: Distribution of 1st MPJ
pooled left and right foot male

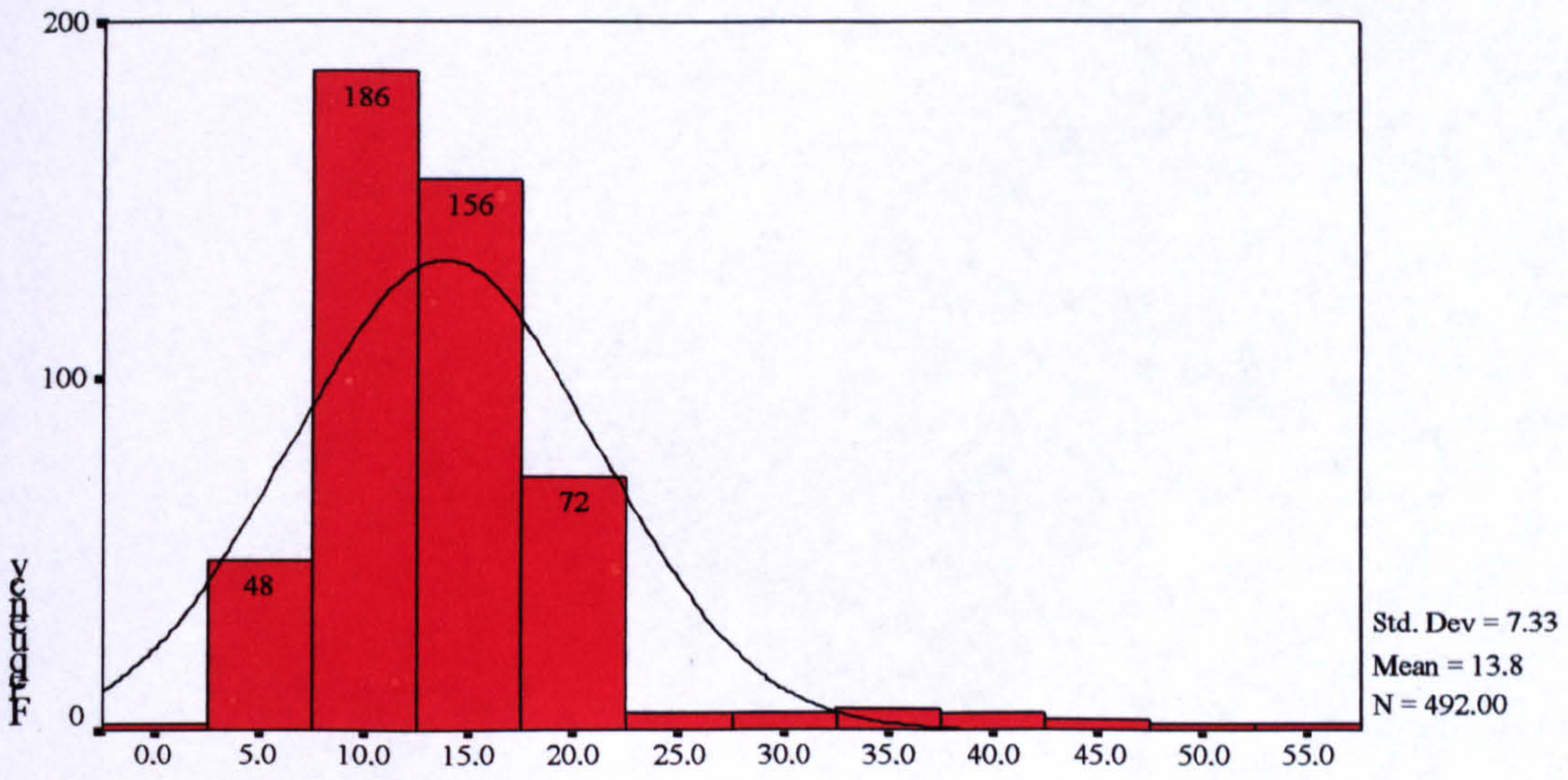


Figure 4.16: Distribution of 1st MPJ angles
pooled left and right foot female data

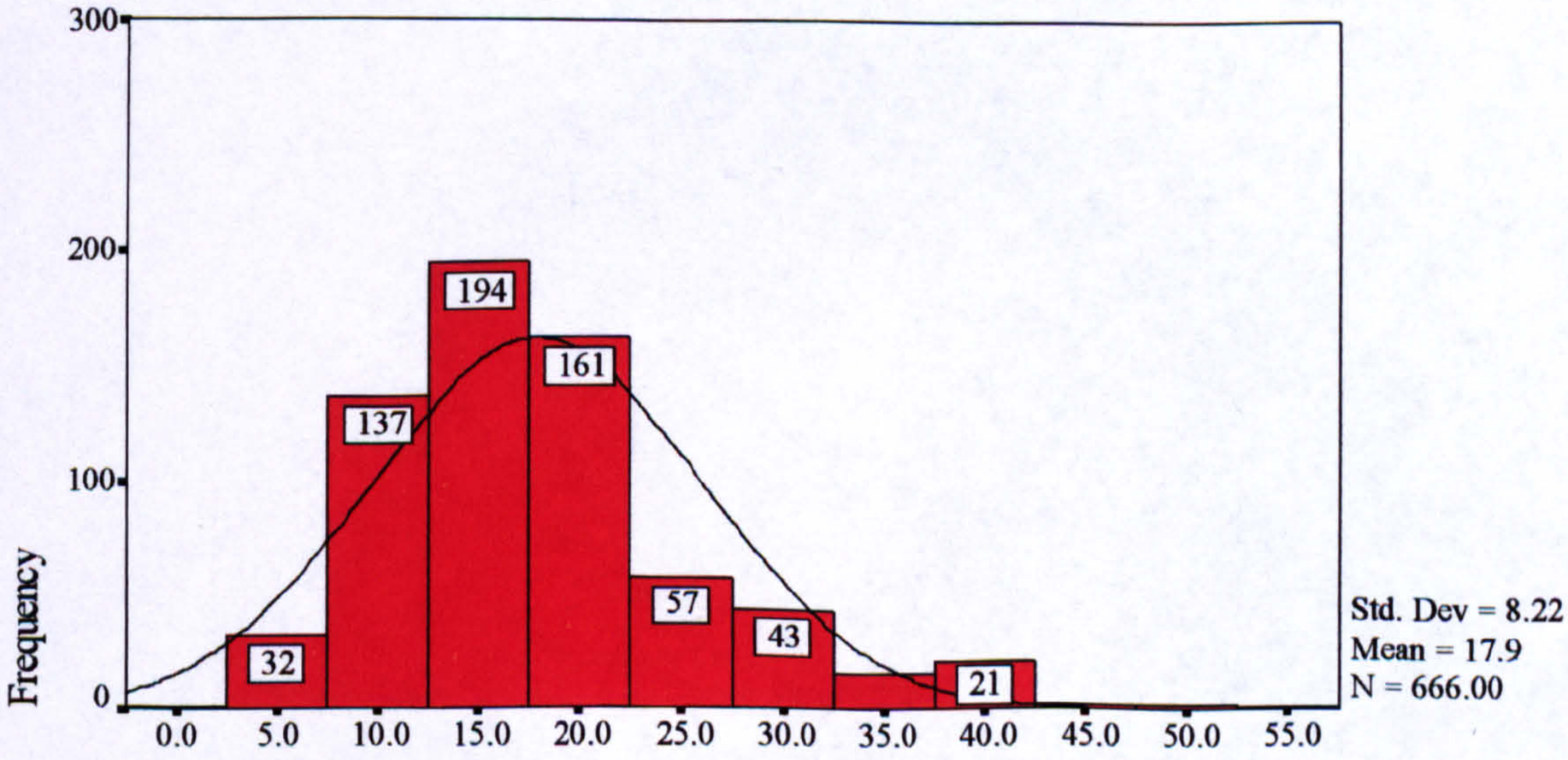


Figure 4.17: Distribution of arch height indices pooled left and right foot male data

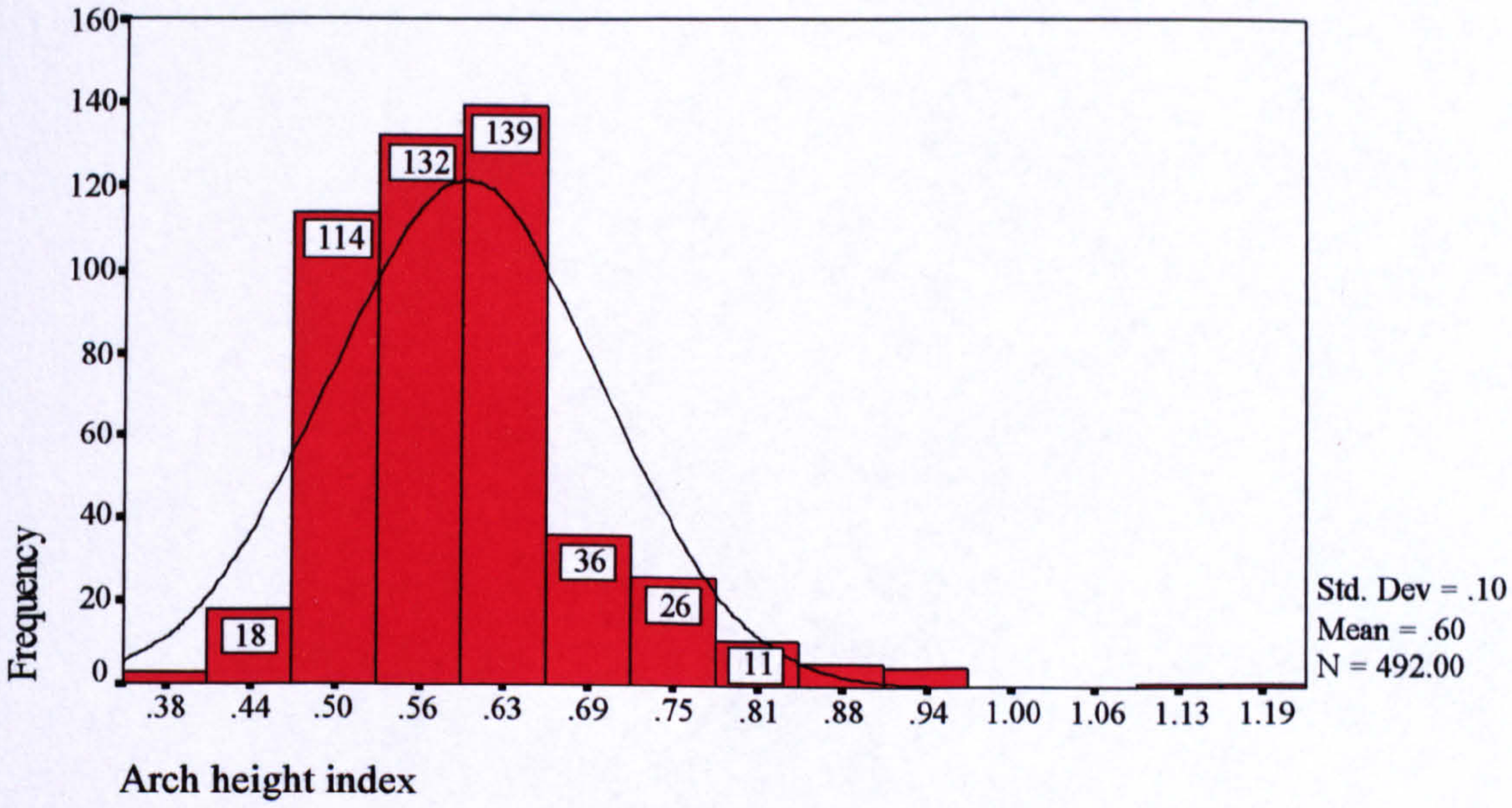


Figure 4.18: Distribution of arch height indices pooled left and right foot female data

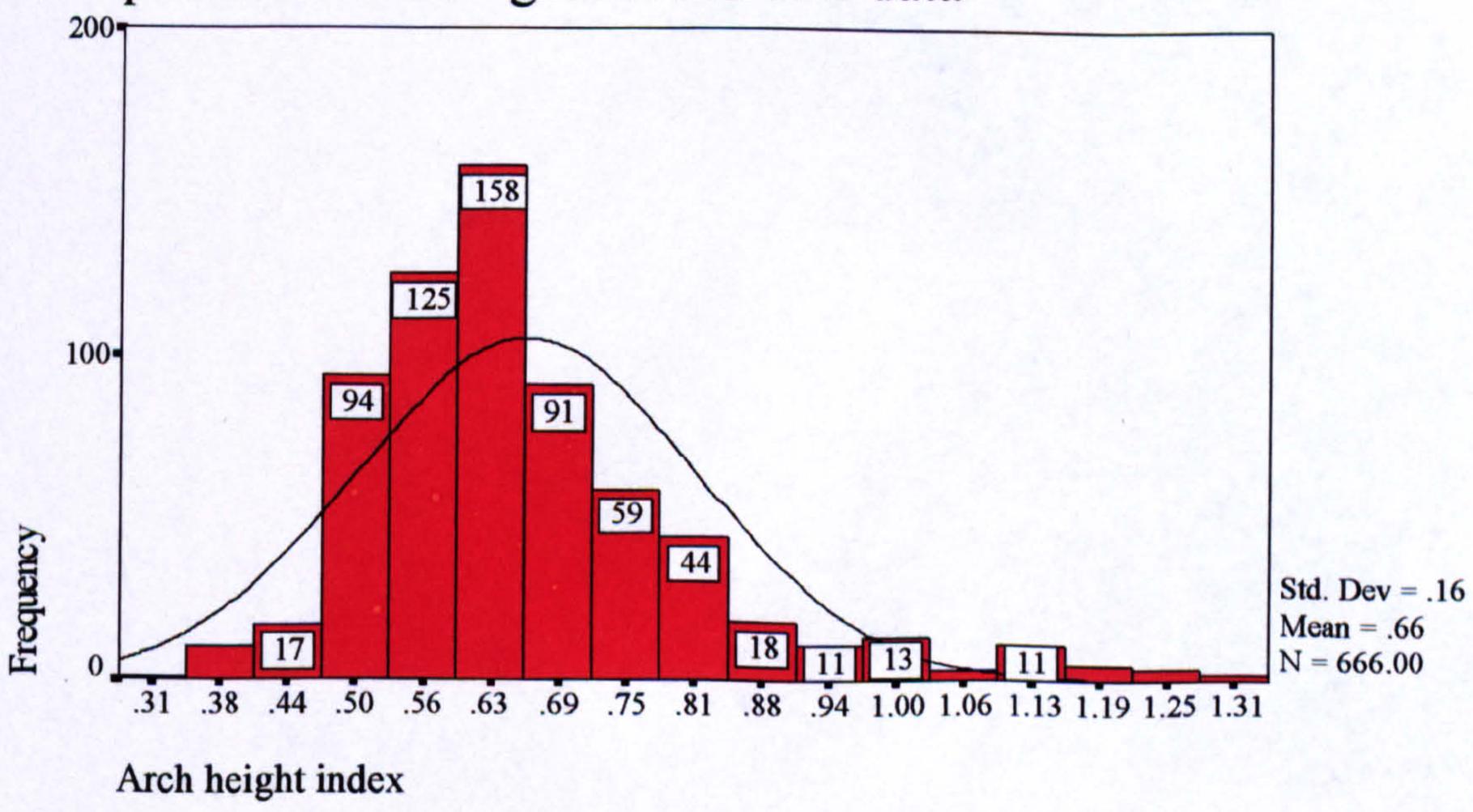


Figure 4.19: Distribution of 1st ray neutral positions pooled left and right foot male data

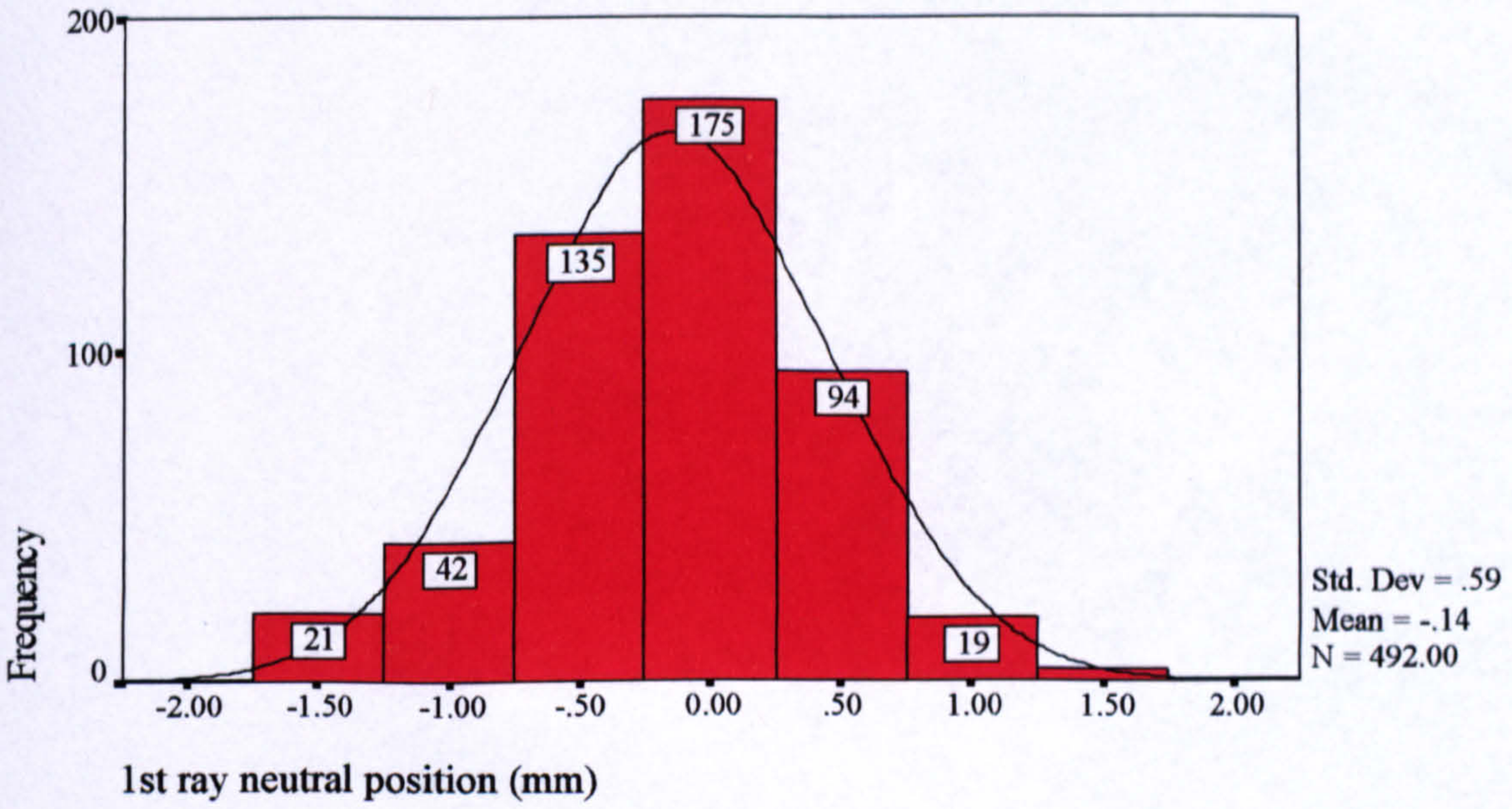


Figure 4.20: Distribution of 1st ray neutral positions pooled left and right foot female data

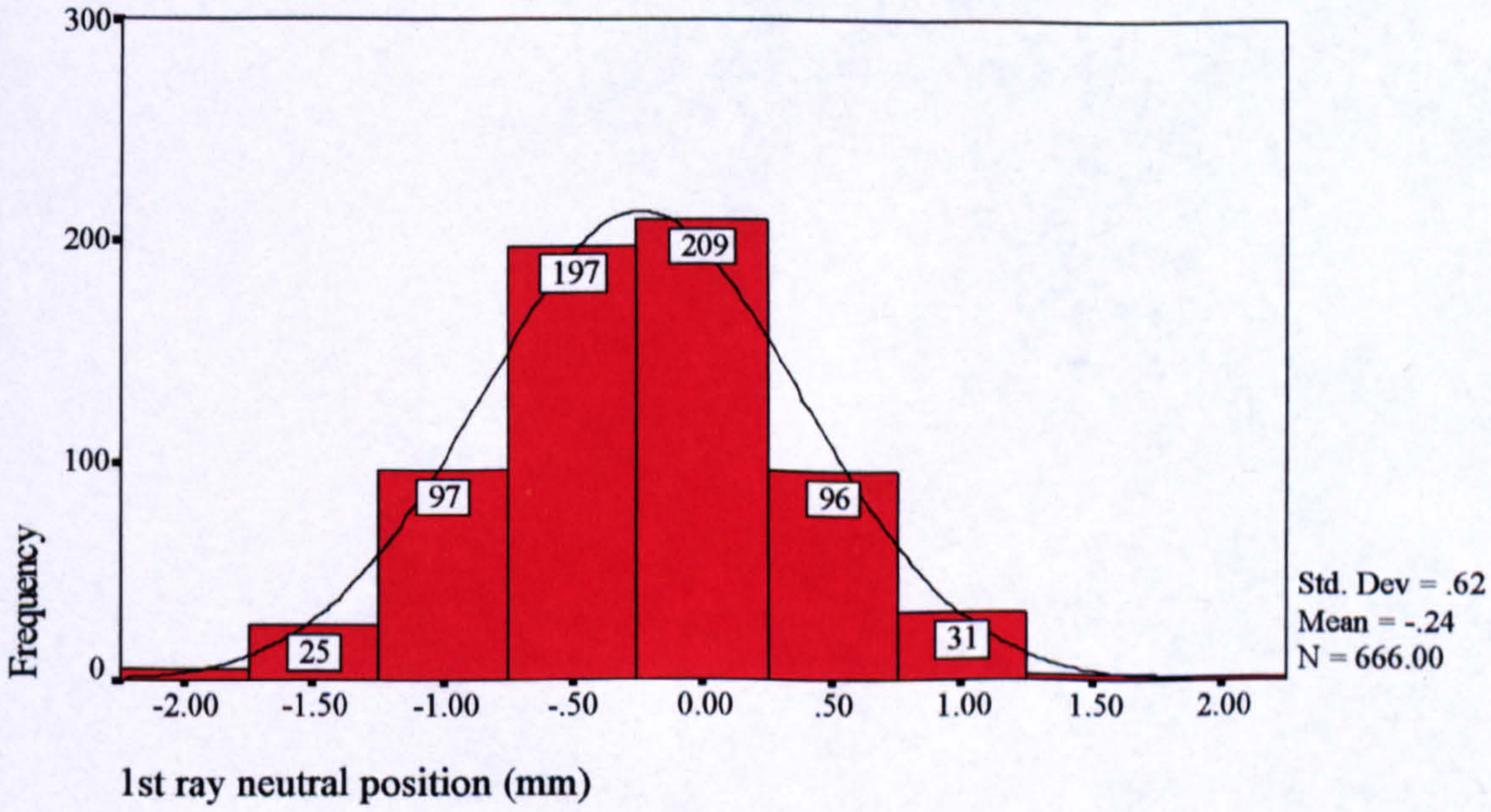


Figure 4.21: Distribution of metatarsal formula scores pooled left and right foot male data

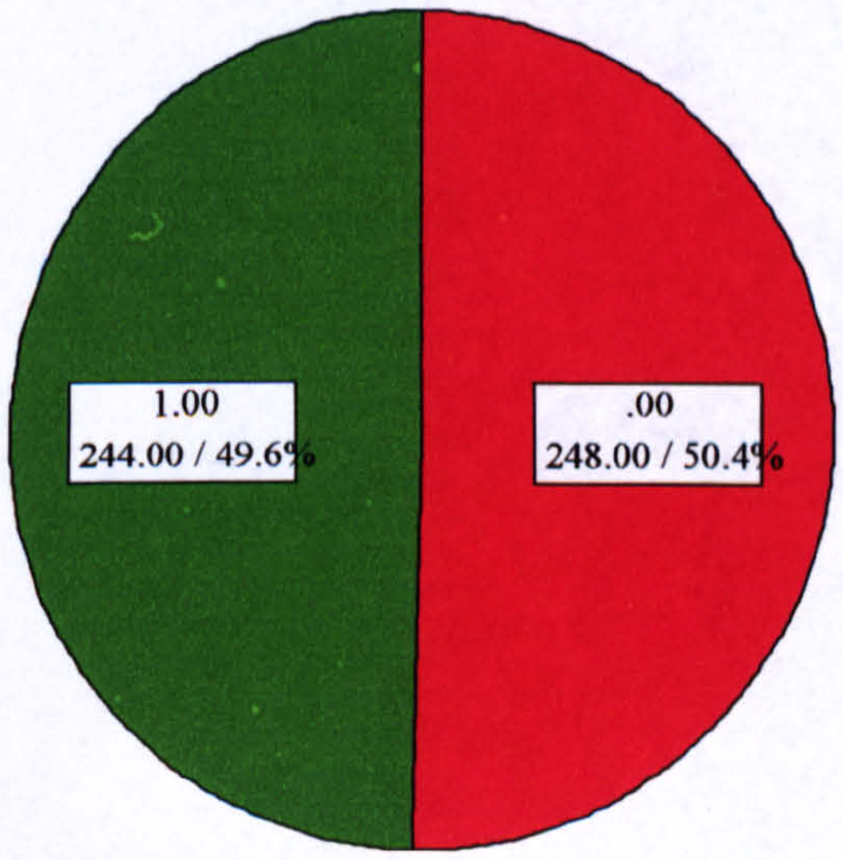


Figure 4.22: Distribution of metarsal formula scores pooled left and right foot female data

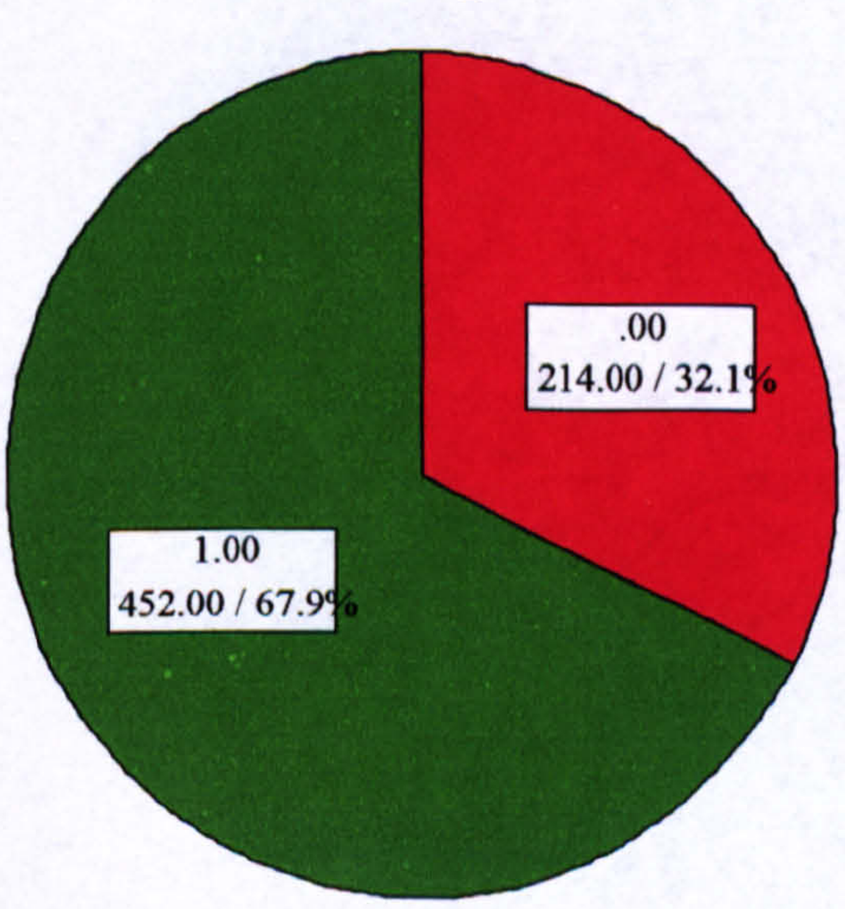


Figure 4.23: Distribution of digital formula scores pooled left and right foot male data

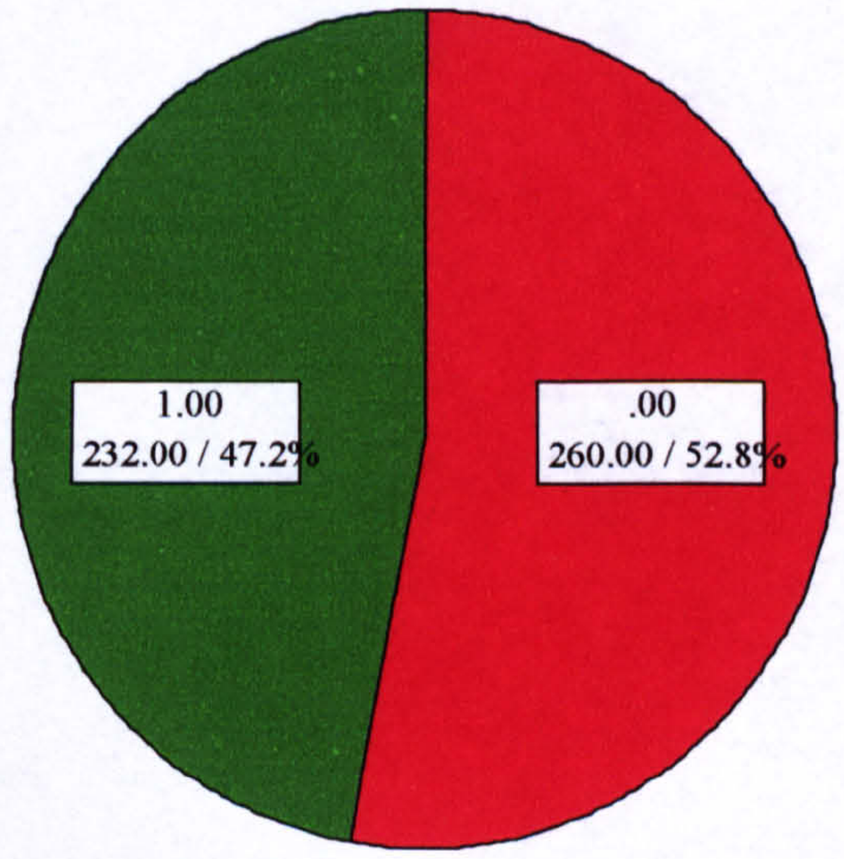


Figure 4.24: Distribution of digital formula scores pooled left and right foot female data

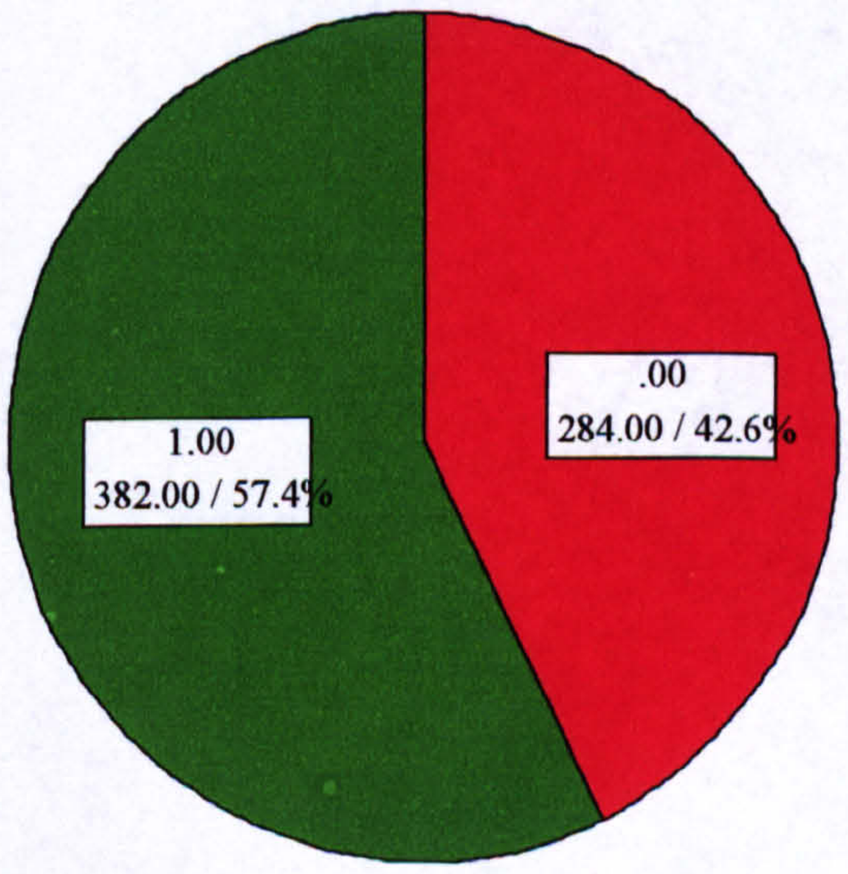


Table 4.4 summarises the results of the two sample unpaired t-test procedures used to examine differences in the parametric data (age, 1st MPJ angle, arch height index and 1st ray neutral position). The results of the Mann-Whitney tests used to examine differences in non-parametric dichotomous data (metatarsal formula and digital formula) are presented in Table 4.5 Statistically significant differences at a level of P=0.05 are indicated by *:

Table 4.4: The results of the two sample unpaired t-test procedure; testing for differences between male and female parametric data.

	Mean ± S.D. female	Mean ± S.D. male	t	df	P
Age	37.1592 ± 20.195	37.7927 ± 22.026	-.51	1156	0.612
1st MPJ angle	17.8844 ± 8.224	13.7988 ± 7.332	8.75	1156	0.000*
AHI	0.6581 ± 0.157	0.5957 ± 0.101	7.72	1156	0.000*
1st RNP	-0.2365 ± 0.624	-0.1402 ± 0.593	-2.65	1156	0.008*

Table 4.5: The results of the non-parametric two unrelated samples Mann-Whitney test procedures; testing for differences between male and female non-parametric data.

	Mean rank female (n=666)	Mean rank male (n=492)	U	Z	P
Metatarsal formula	624.45	518.65	133896.0	-6.2748	0.000*
Digital formula	604.60	545.52	147120.0	-3.4374	0.001*

Although no statistically significant difference was observed in the age data of males and females (P=0.612), significant statistical differences were detected between genders in all of the foot measurement variables. Therefore, regression of offspring on mid-parent values was not valid. Subsequent regression analyses were therefore performed on male offspring and male parent, female offspring on male parent, male offspring on female parent and female offspring and female parent values.

4.5 Age Adjustment

This study aimed to investigate the transmission of several foot characteristics from parents to their offspring, in an attempt to elucidate the relative importance of genetic and environmental influences in the ontogeny of these characteristics. If any of the foot characteristics are age dependent, it is possible that the younger age of the offspring's may mask the true relationship between parent and offspring data, producing less of a correlation between parent and offspring than might otherwise be observed if the effects of age are accounted for. Therefore, it was necessary to investigate the relationship between the foot characteristics and age, and, if necessary, age-adjust offspring data prior to genetic analysis and the estimation of heritability.

It was noted in Section 4.4 that no significant statistical difference existed in the age data of males and females; however, statistically significant differences did exist in the foot measurement variables. Therefore, the relationship between the foot measurement variables and age required independent investigation for the two genders.

Using linear, quadratic and cubic regression analyses the relationships between the foot measurement variables and age were modelled. The results of this procedure are given in Tables 4.6 and 4.7 for male and female data respectively.

Table 4.6 The results of regression analyses; modelling the relationships between the foot measurement variables and age. Male data.

REGRESSION	R^2	F	SIGNIFICANCE F
1st MPJ angle on Age			
Linear	0.364	279.978	0.000
Quadratic	0.365	140.537	0.000
Cubic	0.393	105.392	0.000
AHI on Age			
Linear	0.170	100.564	0.000
Quadratic	0.295	102.170	0.000
Cubic	0.297	68.711	0.000
1st RNP on Age			
Linear	0.019	9.686	0.002
Quadratic	0.026	6.408	0.002
Cubic	0.026	4.267	0.006
Metatarsal formula on Age			
Linear	0.023	11.992	0.001
Quadratic	0.026	6.458	0.002
Cubic	0.036	6.022	0.001
Digital formula on Age			
Linear	0.008	3.964	0.047
Quadratic	0.015	3.784	0.023
Cubic	0.016	2.694	0.046

Table 4.7: The results of regression analyses; modelling the relationships between the foot measurement variables and age. Female data.

REGRESSION	R^2	F	SIGNIFICANCE F
1st MPJ angle on Age			
Linear	0.421	482.535	0.000
Quadratic	0.423	242.615	0.000
Cubic	0.445	177.052	0.000
AHI on Age			
Linear	0.355	365.591	0.000
Quadratic	0.464	286.532	0.000
Cubic	0.467	193.250	0.000
1st RNP on Age			
Linear	0.034	23.029	0.000
Quadratic	0.034	11.644	0.000
Cubic	0.035	7.909	0.000
Metatarsal formula on Age			
Linear	0.043	30.153	0.000
Quadratic	0.047	16.149	0.000
Cubic	0.054	12.612	0.000
Digital formula on Age			
Linear	0.036	24.882	0.000
Quadratic	0.044	15.359	0.000
Cubic	0.045	10.278	0.000

Examination of Tables 4.6 and 4.7 revealed that all variables displayed relationships with age, but of varying strengths, as indicated by the r^2 values. 1st RNP, metatarsal formula and digital formula displayed only weak relationships with age, with r^2 values <0.1. Such relationships must be considered as negligible and age adjustment of these variables was not considered necessary. 1st MPJ angle and AHI displayed stronger relationships with age and consequently age adjustment of these variables was necessary.

The cubic models had the highest r^2 values and therefore were the best fitting models. This was predictable since the additional coefficients estimated by the cubic model inevitably results in a better fit. However, the addition of coefficients results in a reduction of degrees of freedom. Norusis (1993) suggests that the use of models with unnecessary coefficients should be discouraged and that cubic models should only be applied when they offer significant advantages over linear or quadratic models.

Examination of r^2 values for the models revealed that only small increases in r^2 (< 0.15) occurred with the addition of coefficients and consequential loss of degrees of freedom. Based on this evidence, the use of cubic models to age-adjust 1st MPJ angles and AHI was rejected in favour of linear models and linear age-adjustments of these variables were performed. Graphical representation of these linear models are given in Figures 4.25- 4.28.

Figure 4.25: Linear regression of 1st MPJ angle on age male data

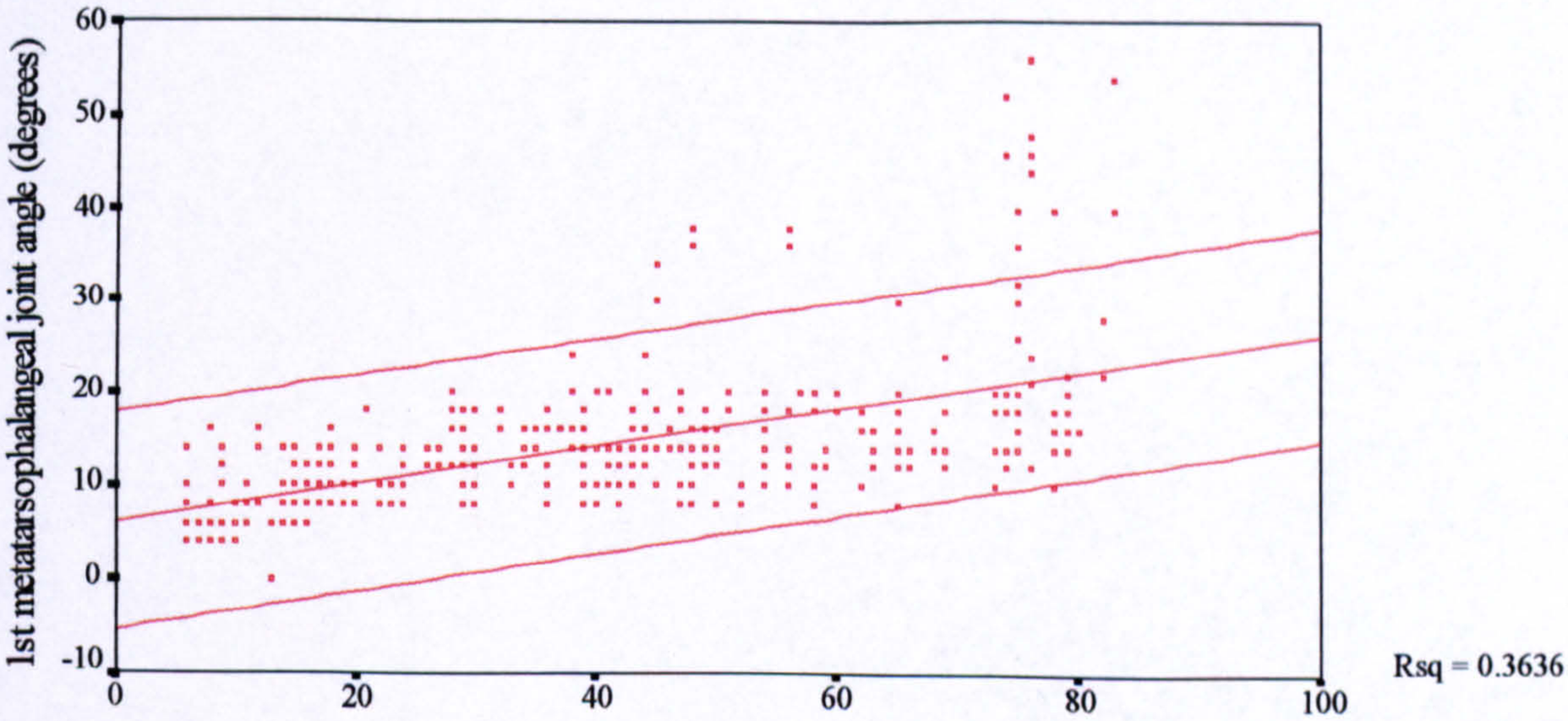


Figure 4.26: Linear regression of 1st MPJ angle on age female data

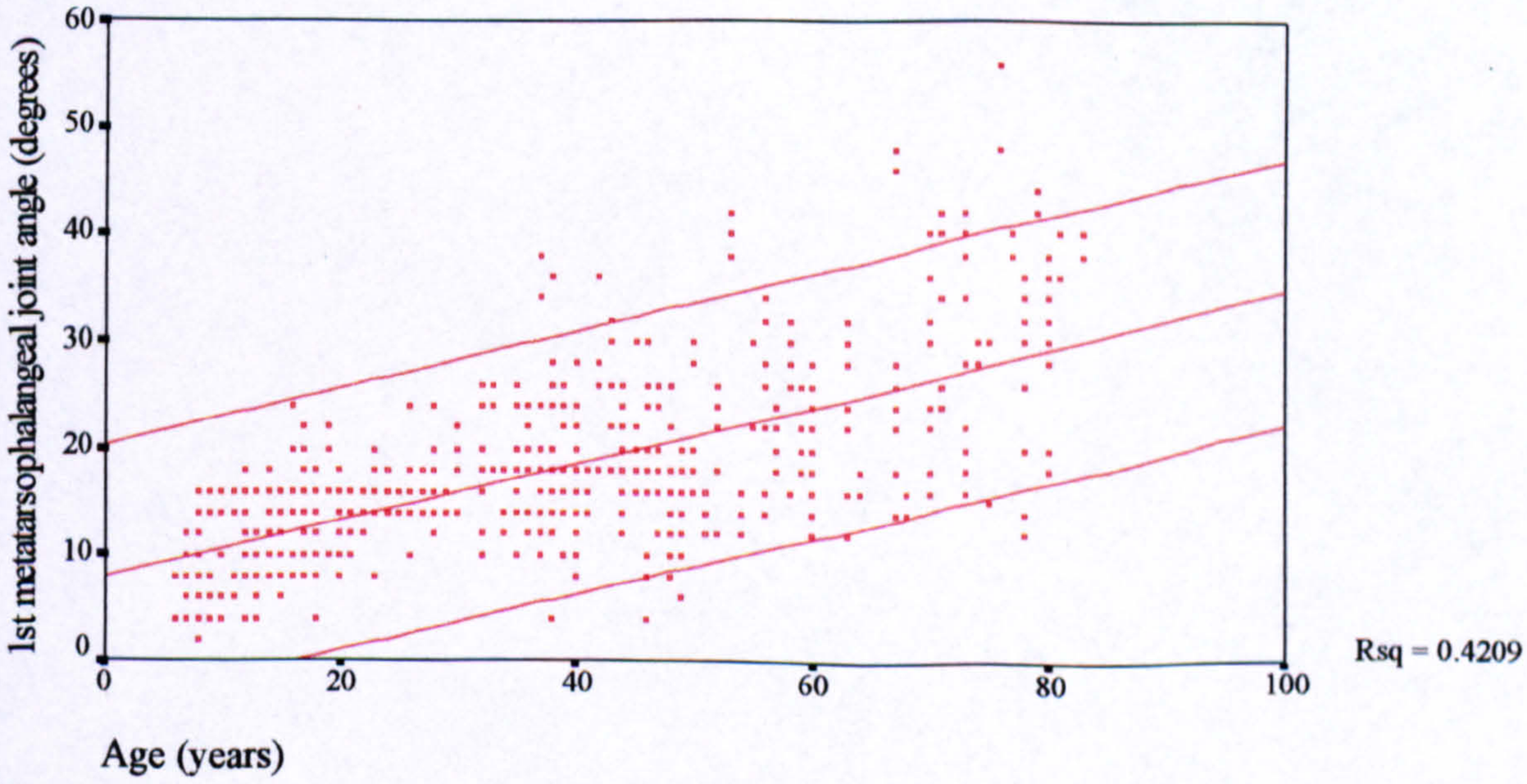


Figure 4.27: Linear regression of arch height index on age male data

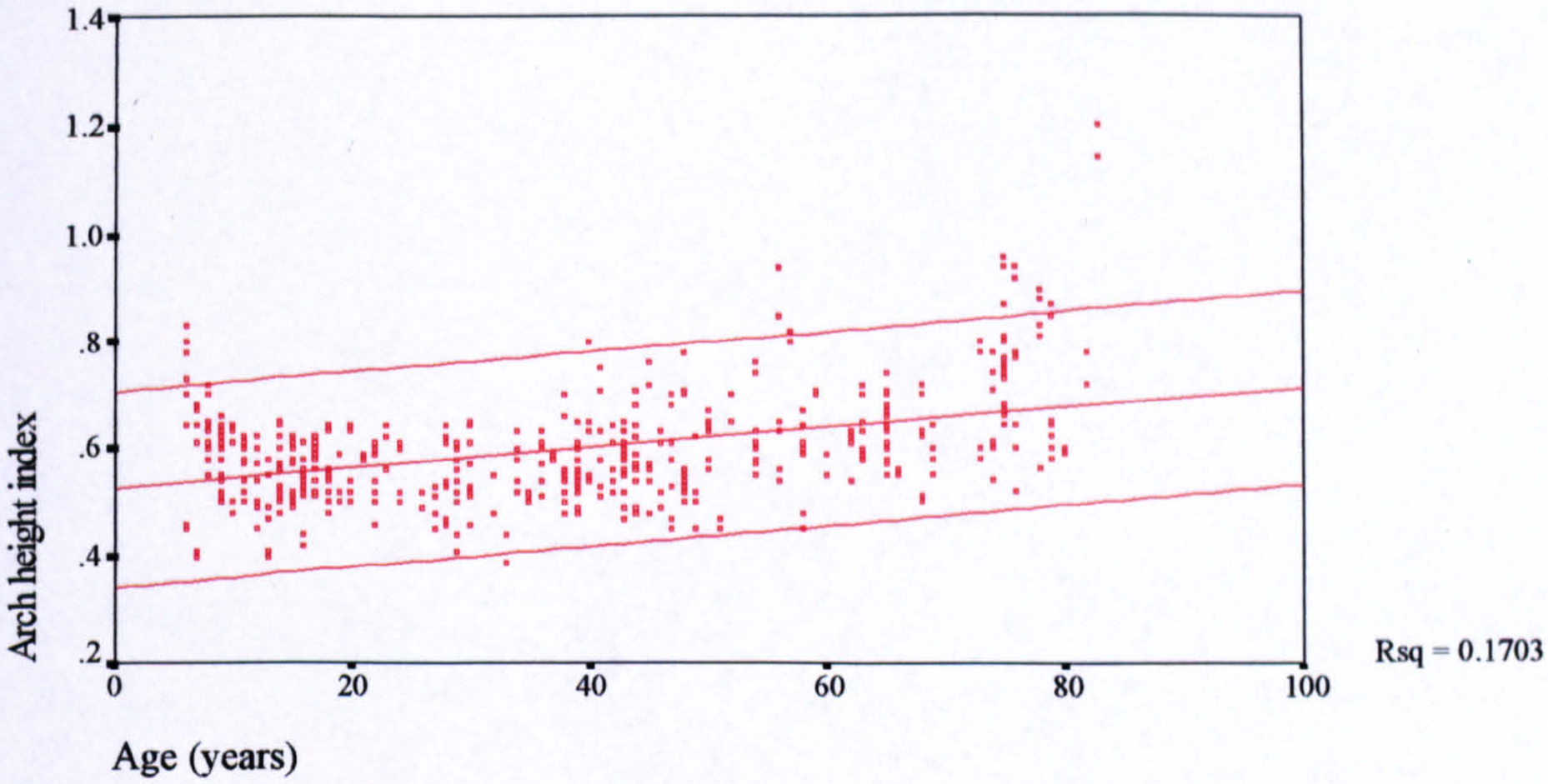
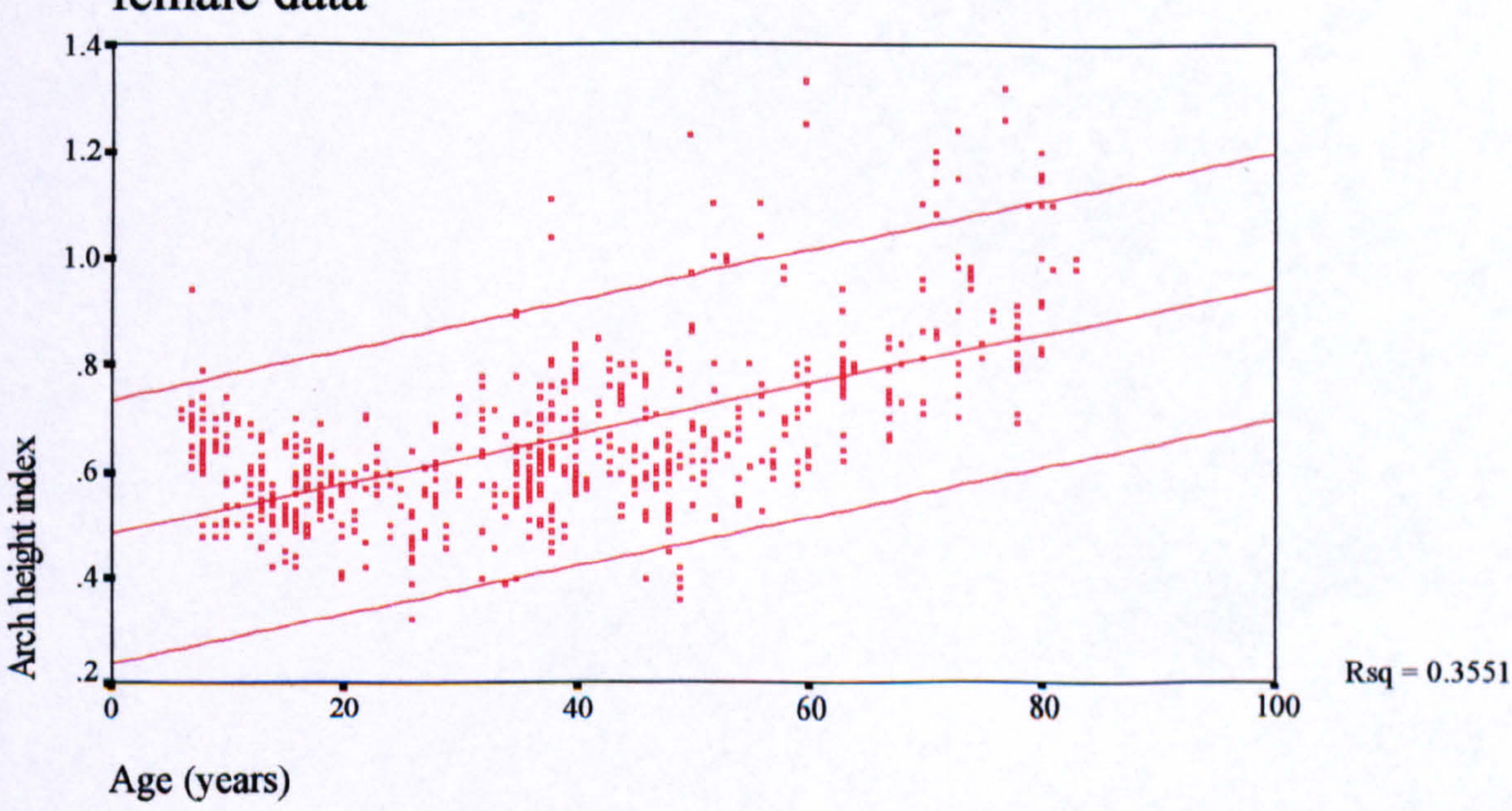


Figure 4.28: Linear regression of arch height index on age female data



Using the information obtained from the curve estimation procedure, the age adjustment factors for offspring data were calculated using:

(Equation 4.3)

$$\delta Y = (b1\ \delta X)$$

Where:
δY= adjustment factor
b1= linear regression coefficient
δX= difference between offspring age and parent age

Addition of the adjustment factor (δY) to the original offspring data yields the adjusted offspring property (i.e. adjusted offspring 1st MPJ angle = offspring 1st MPJ angle + δY).

Thus, offspring data for 1st MPJ angle and AHI was adjusted to their expected values at the age of the parent. Clearly, when data from both parents was available, two adjustments were necessary, one corresponding to an adjustment to the father's age and one to an adjustment to the mother's age.

4.6 Estimation of Heritability

It was noted in Section 3.5.6 that the degree of resemblance between relatives is given by the regression of offspring on parents (Equation 3.20). Moreover, the regression of offspring on parents provides the means of estimating the proportionate amount of additive genetic variance, V_A / V_P or narrow sense heritability of a given trait.

For the offspring on parent regression analyses, data was organised in spreadsheet form into columns representing male parents, female parents, male offspring and female offspring. When more than one offspring of the same gender existed within a family group, the parents and the subsequent offspring were re-entered. This allowed the regression of all offspring of the same gender to be carried out in one analysis, regardless of birth order. In the case of larger family groups where grandparents and great-grandparents of offspring had been measured, these relatives where paired with their own offspring. Thus, some subjects were entered both as parent and offspring. For example, in a family consisting of 2 male offspring, 1 female parent and 1 female grandparent, three analyses were performed: regression of the parent on grandparent (the parent is the offspring and the grandparent the parent), regression of the first male offspring on the parent and regression of the second male offspring on the parent. In this

example the parent value is entered three times. Clearly, it is possible to calculate heritability from the more distant relationships between offspring and grandparent and offspring and great-grandparent. However, Falconer (1989) suggests that, in general, the closer the relationship, the more precise the estimate. Moreover, the sample size for these analyses would have been very small.

The linear regression procedure was used to determine the regression of male offspring on male parent, female offspring on male parent, male offspring on female parent and female offspring on female parent for the foot measurements. Analyses of 1st MPJ angle and AHI data was performed between the age adjusted offspring data and parental data. It was demonstrated in section 4.4 that statistically significant differences existed in data obtained from males and females. Thus, regression of offspring data on mid-parent values was not performed. Analysis of this nature is inappropriate when differences exist in variances of data between genders (Falconer 1989). All analysis were performed on pooled left and right foot data. Graphical representation of the analyses is given in Figures 4.29- 4.48. Summary and analysis of variance statistics for the analyses are given in Appendix 3.

Figure 4.29: Linear regression of age adjusted male offsprings on male parents

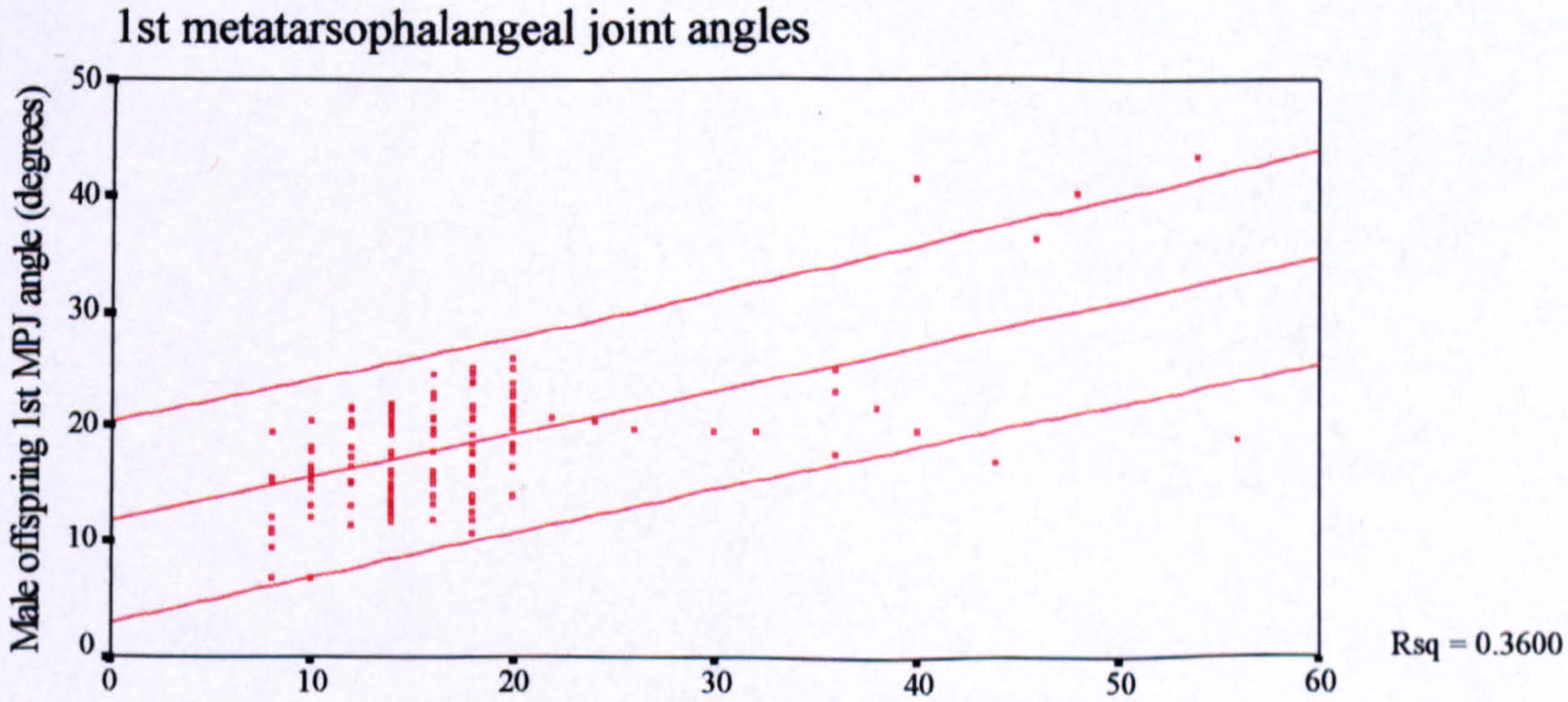


Figure 4.30: Linear regression of
age adjusted female offsprings on male parents

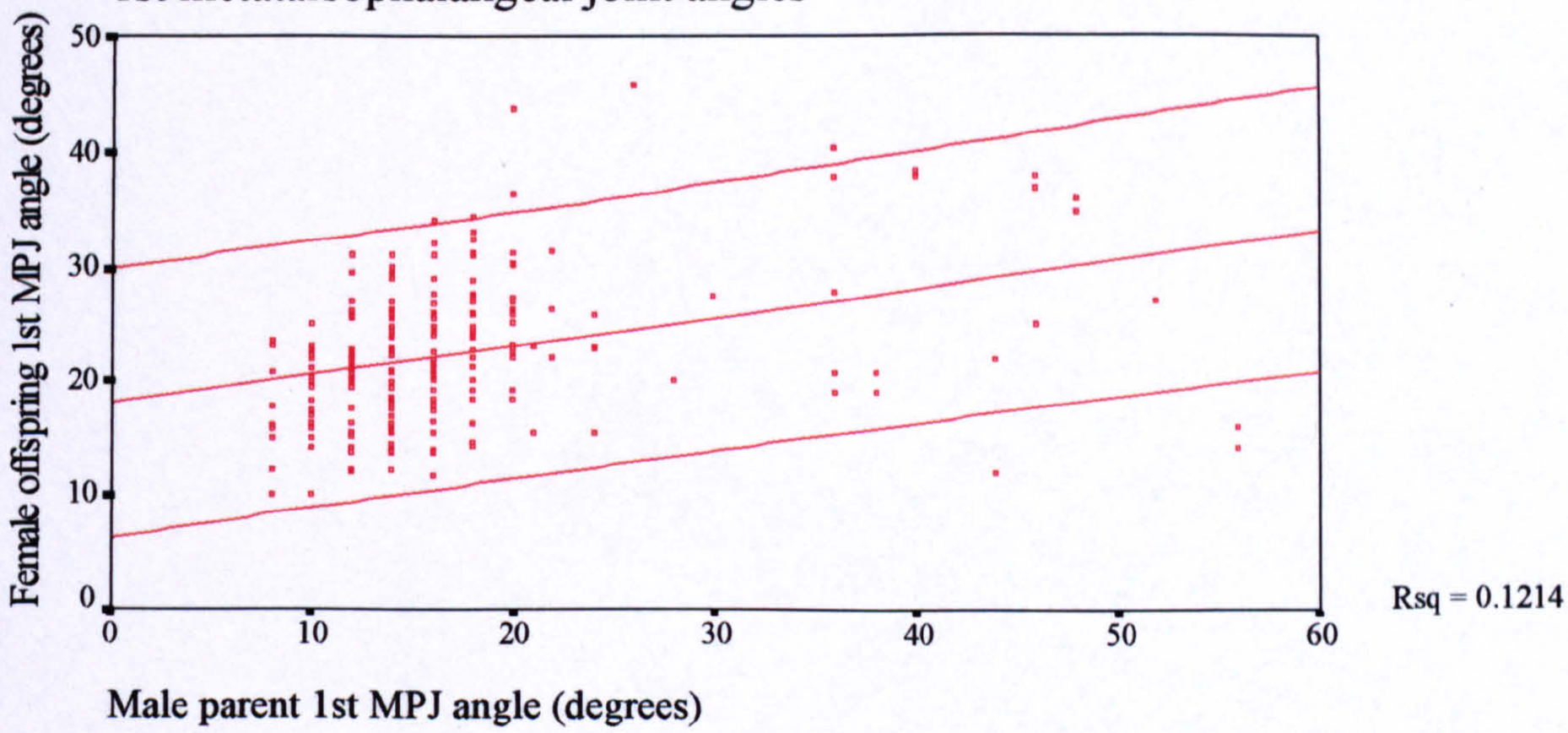


Figure 4.31: Linear regression of
age adjusted male offsprings on female parents

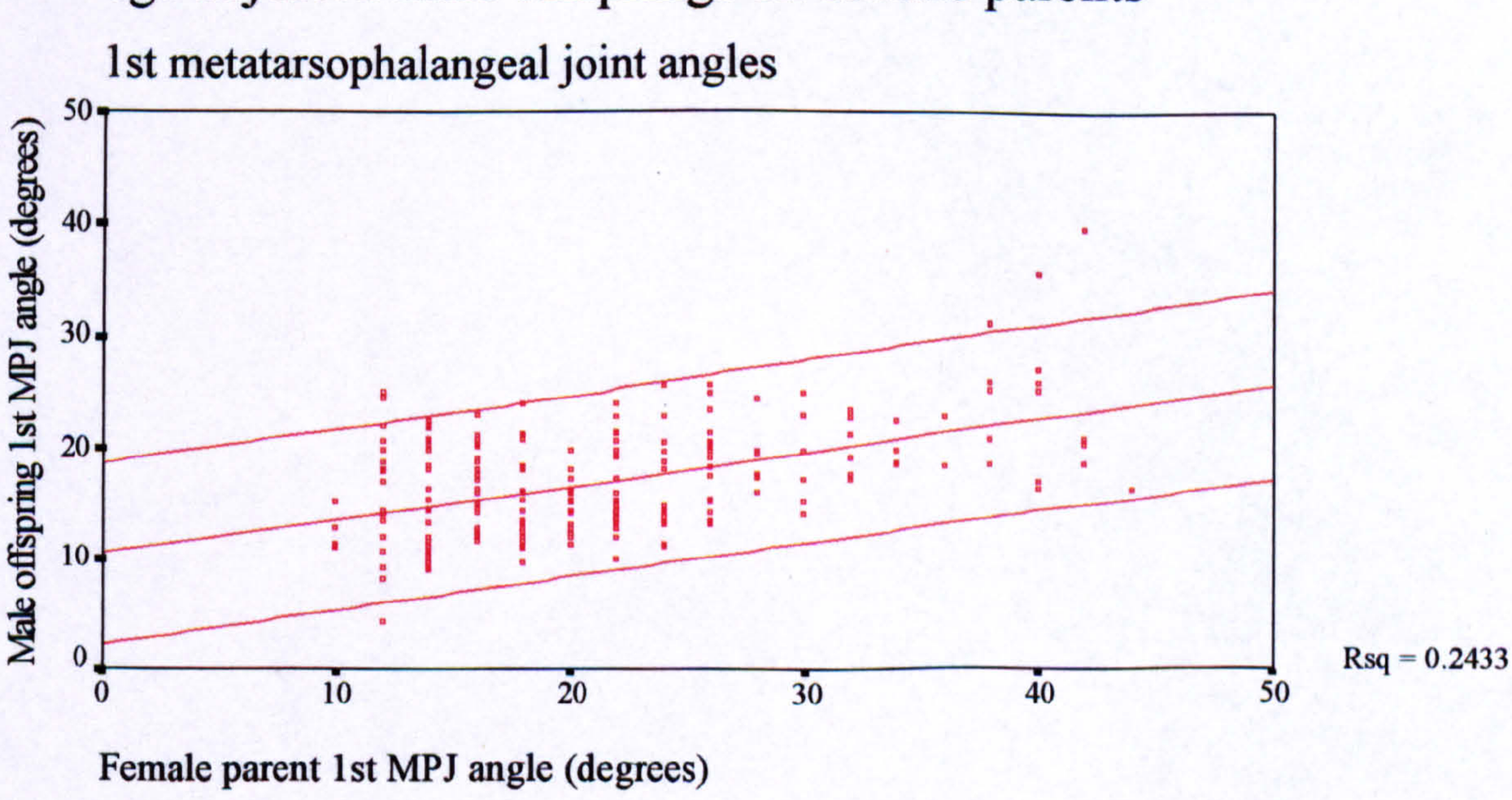


Figure 4.32: Linear regression of
age adjusted female offsprings on female parents

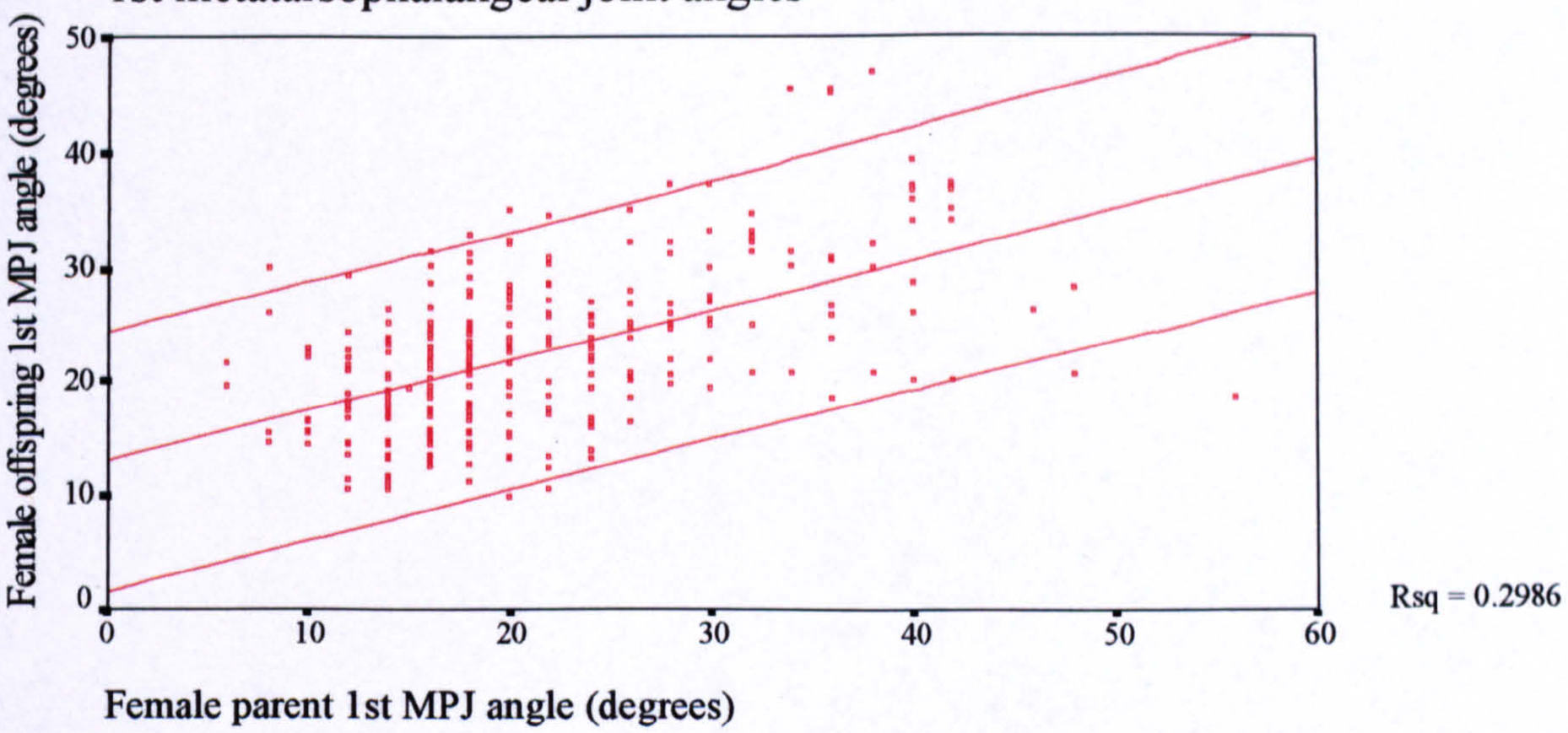


Figure 4.33: Linear regression of
age adjusted male offsprings on male parents

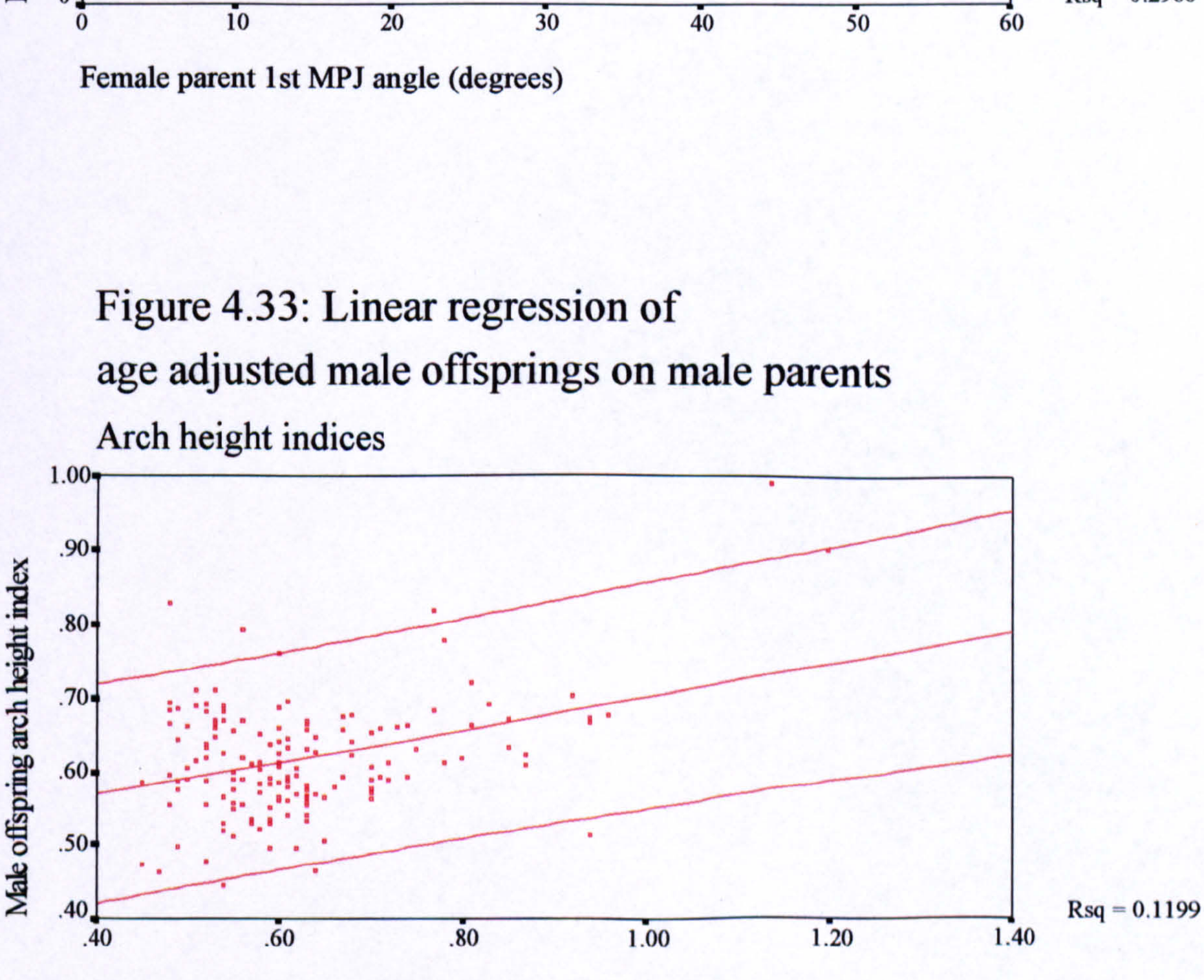


Figure 4.34: Linear regression of
age adjusted female offsprings on male parents

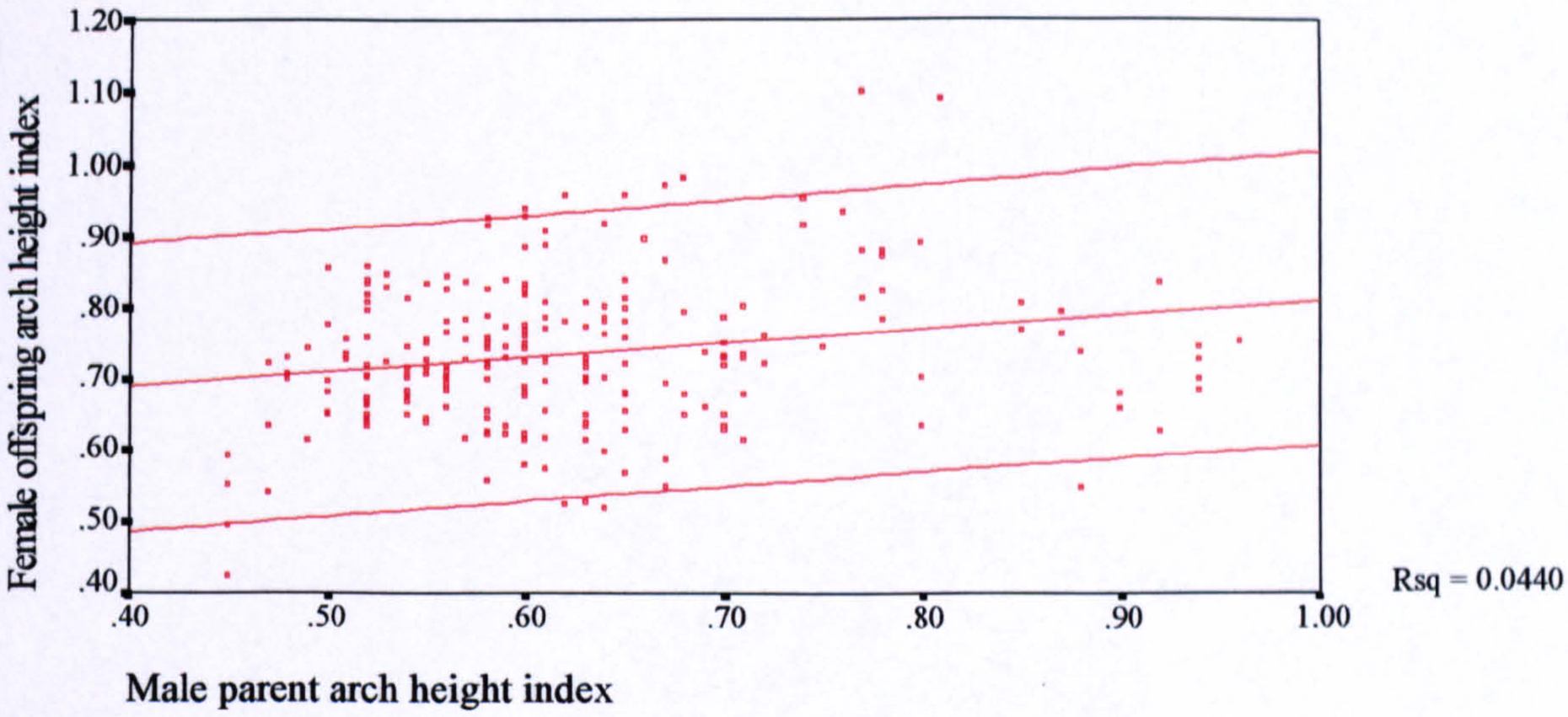


Figure 4.35: Linear regression of
age adjusted male offsprings on female parents

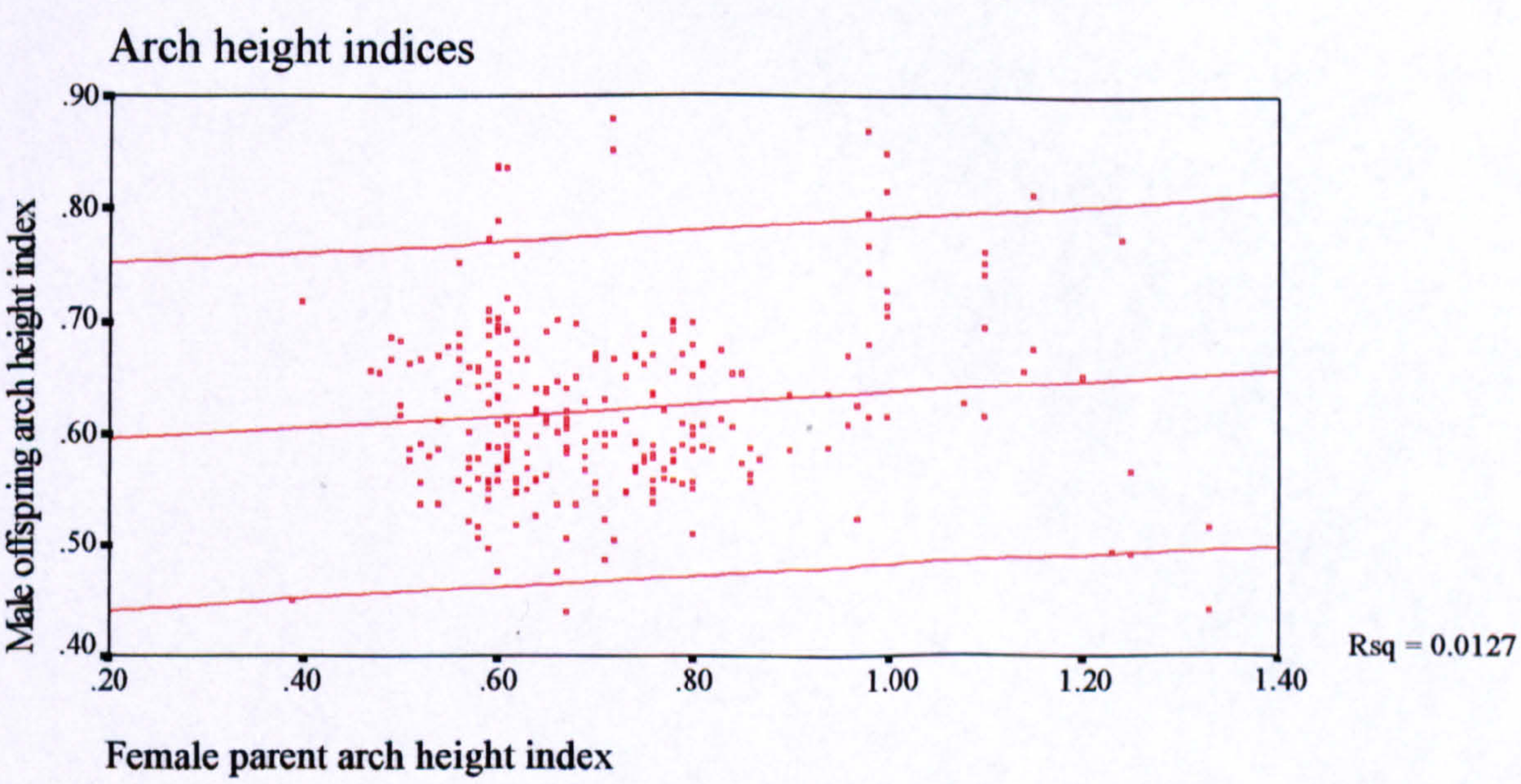


Figure 4.36: Linear regression of
age adjusted female offsprings on female parents

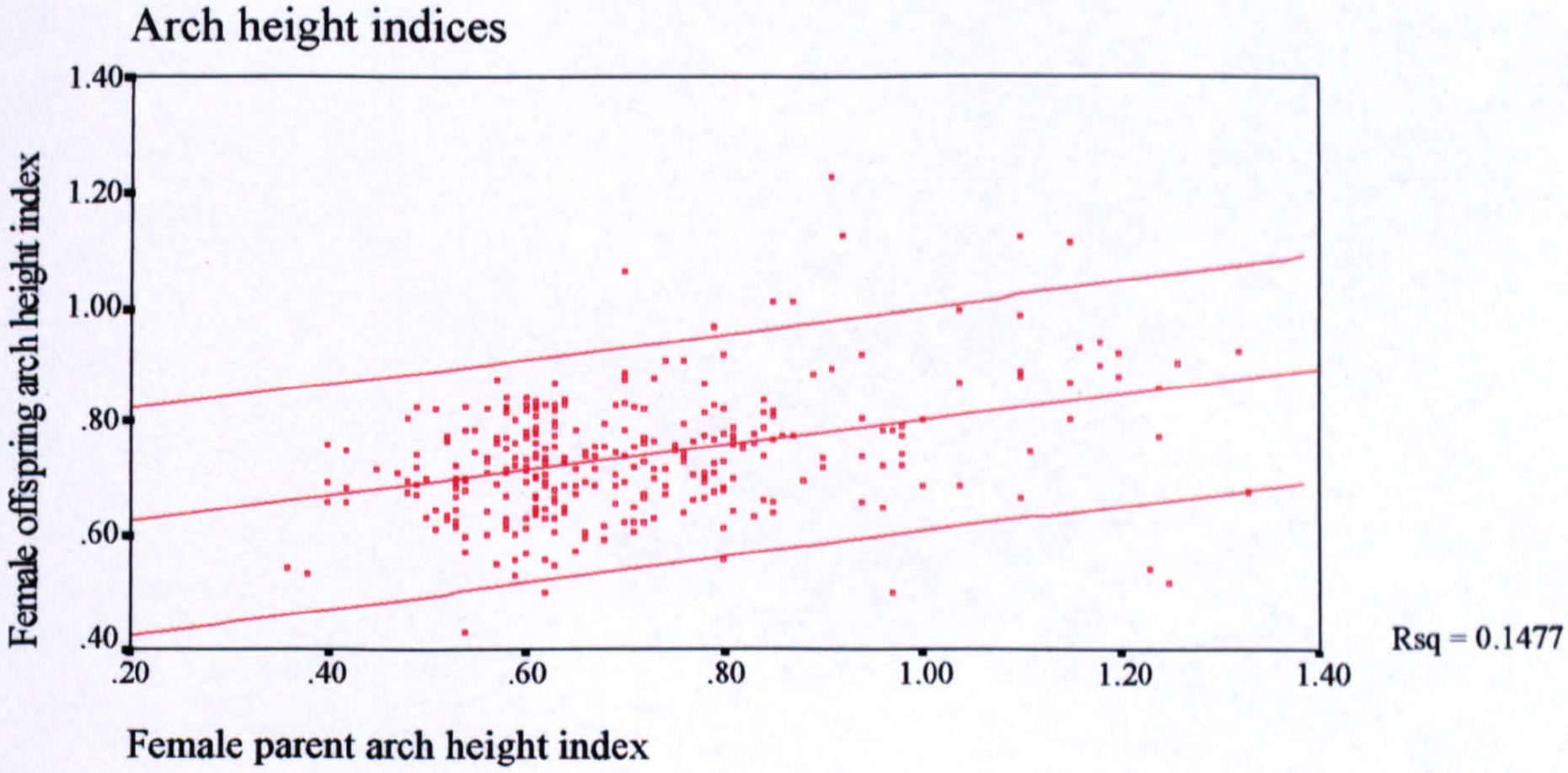


Figure 4.37: Linear regression of
male offsprings on male parents

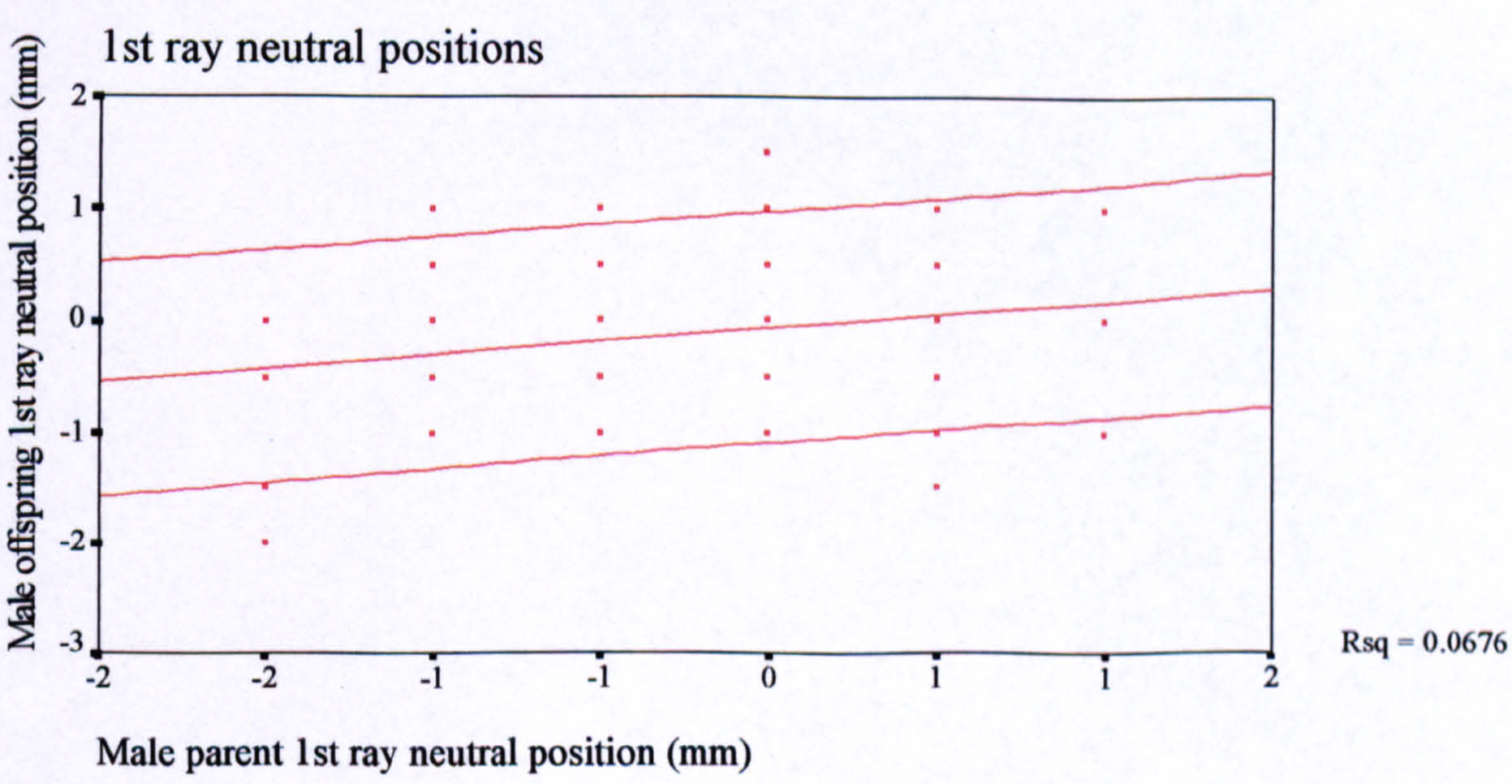


Figure 4.38: Linear regression of female offsprings on male parents

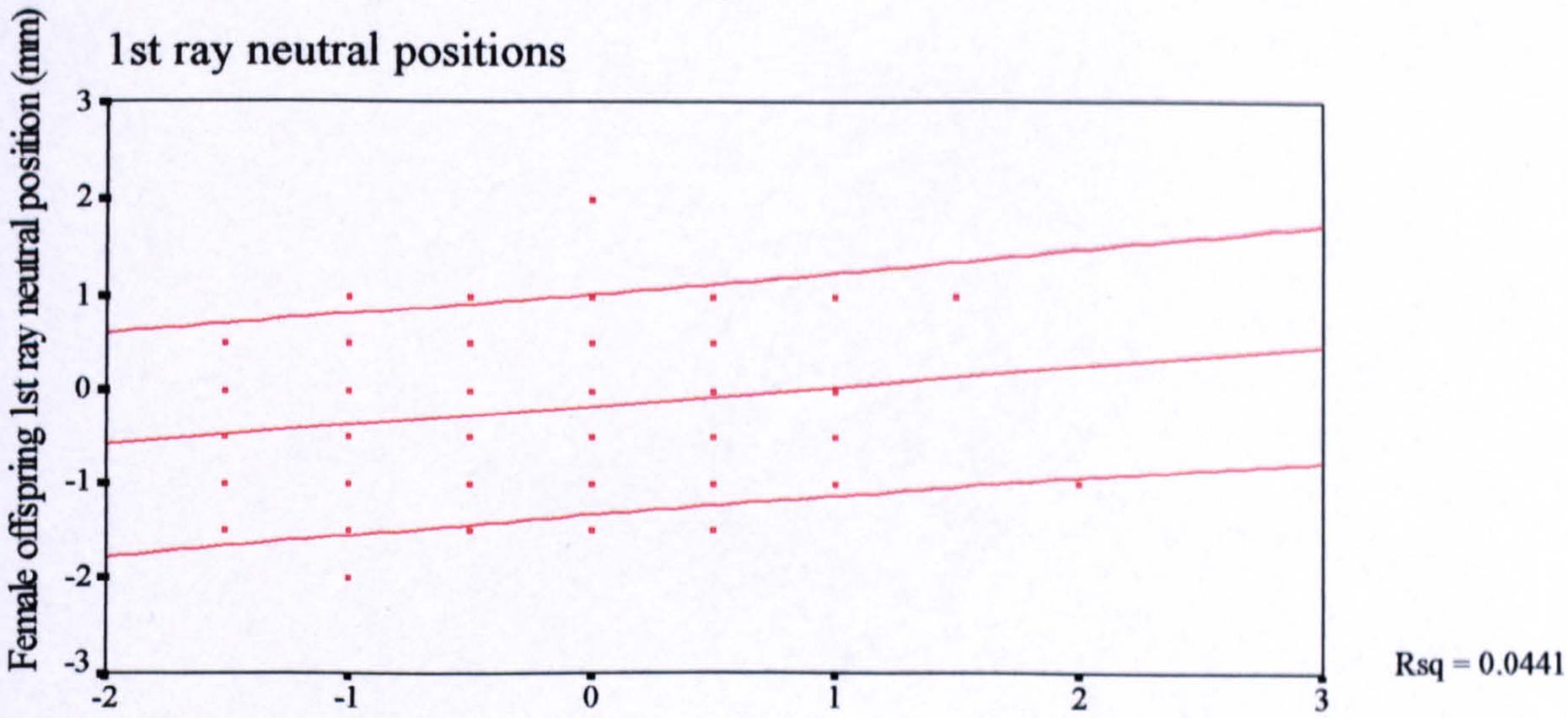


Figure 4.39: Linear regression of male offsprings on female parents

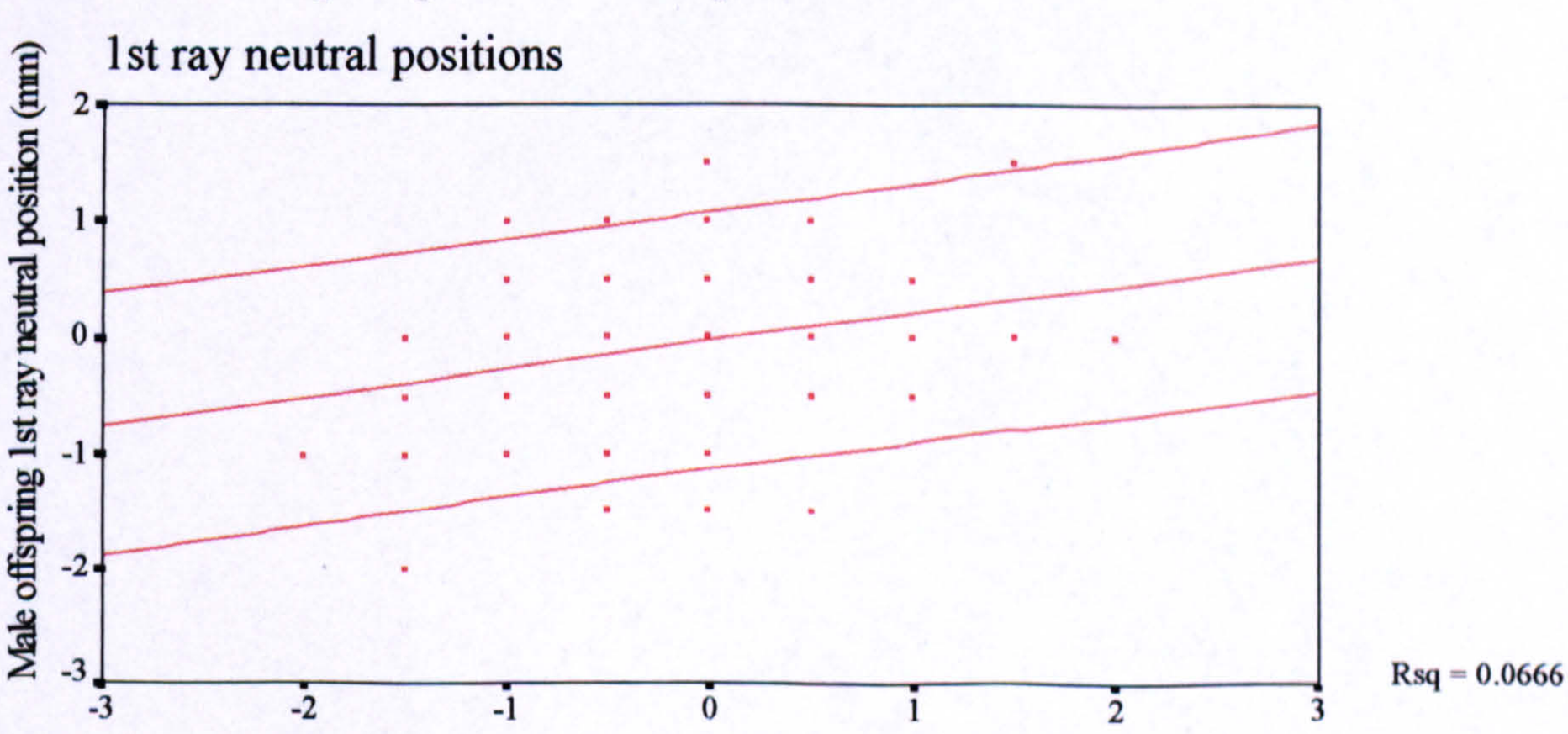


Figure 4.40: Linear regression of female offsprings on female parents

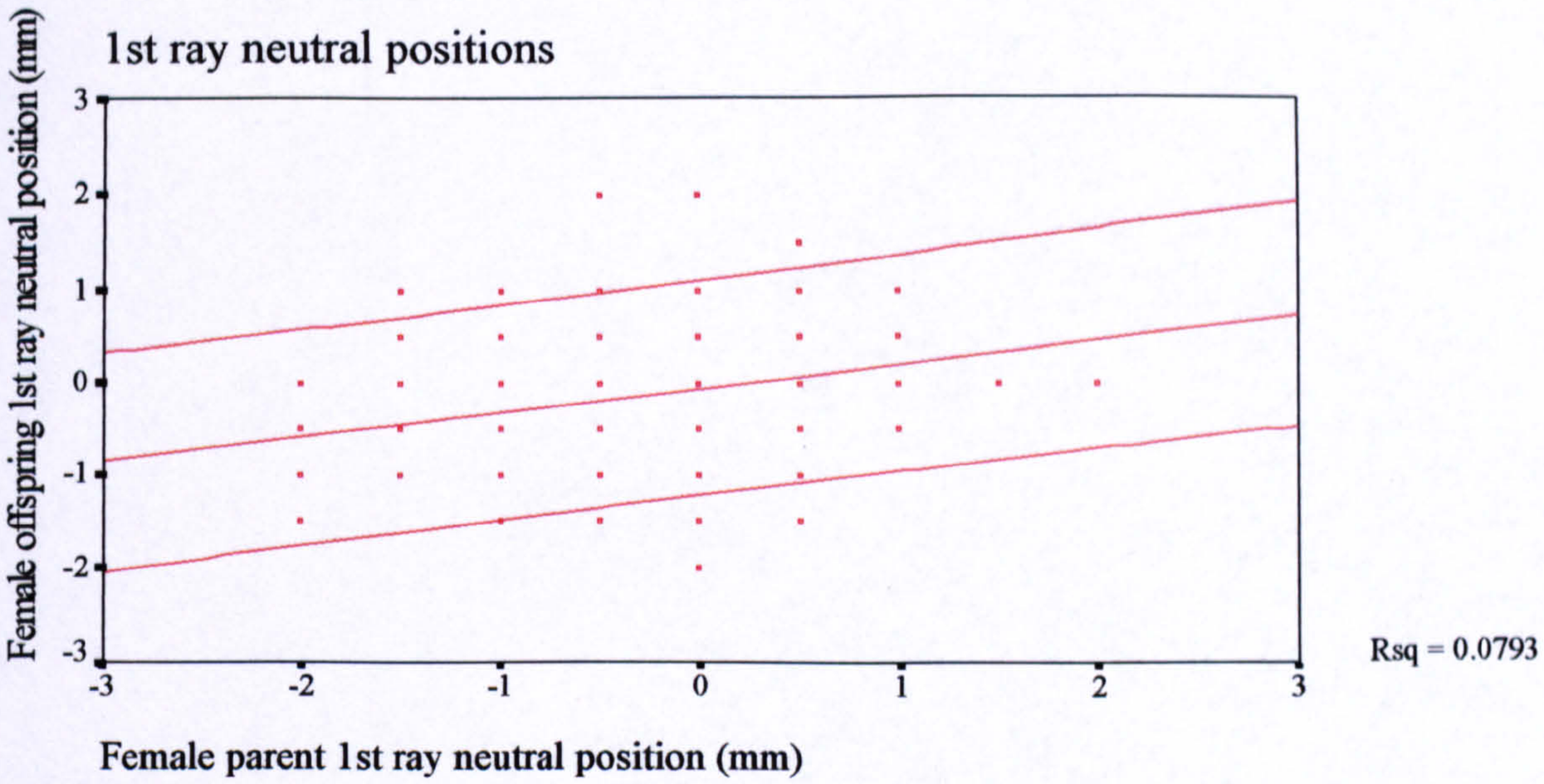


Figure 4.41: Linear regression of male offsprings on male parents

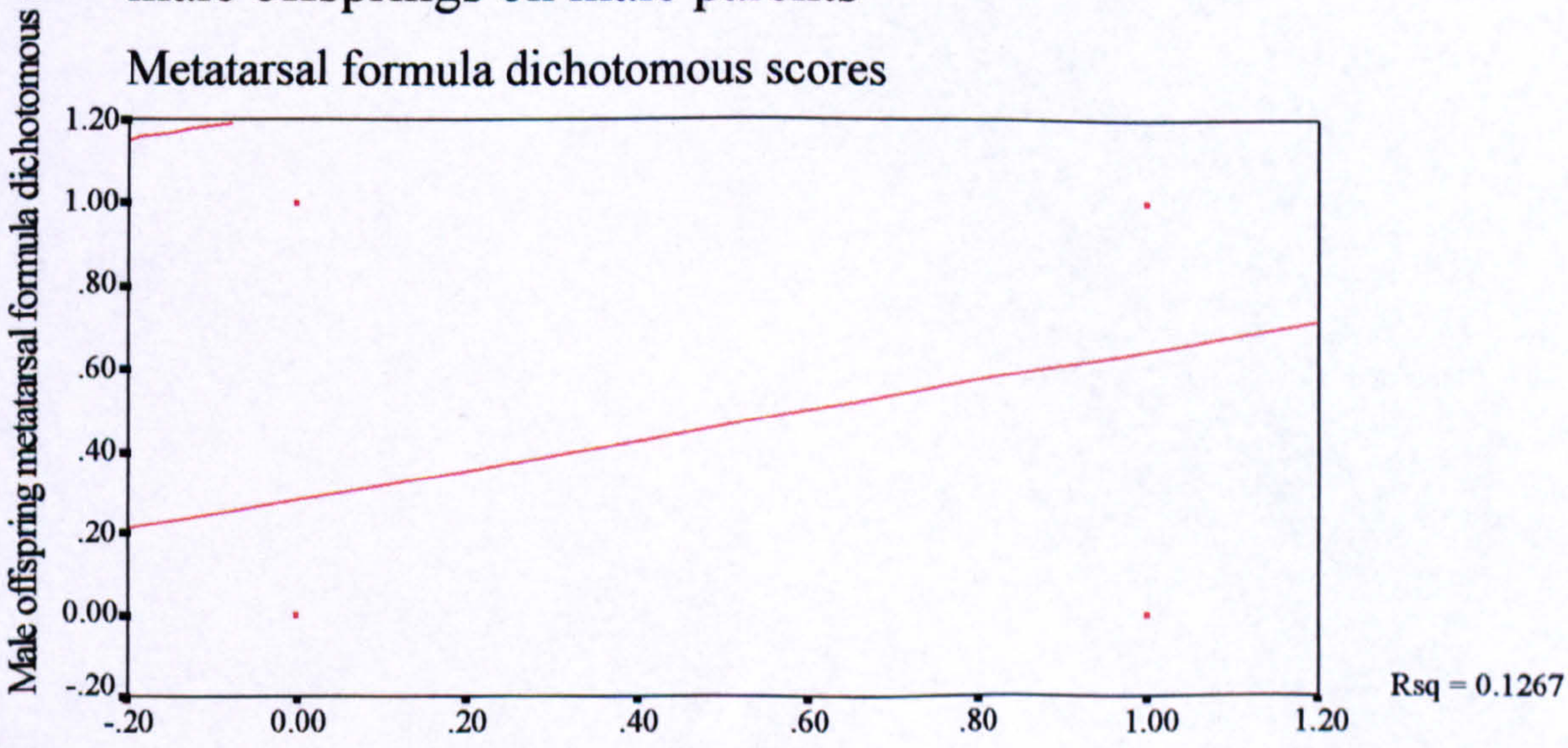


Figure 4.42: Linear regression of female offsprings on male parents

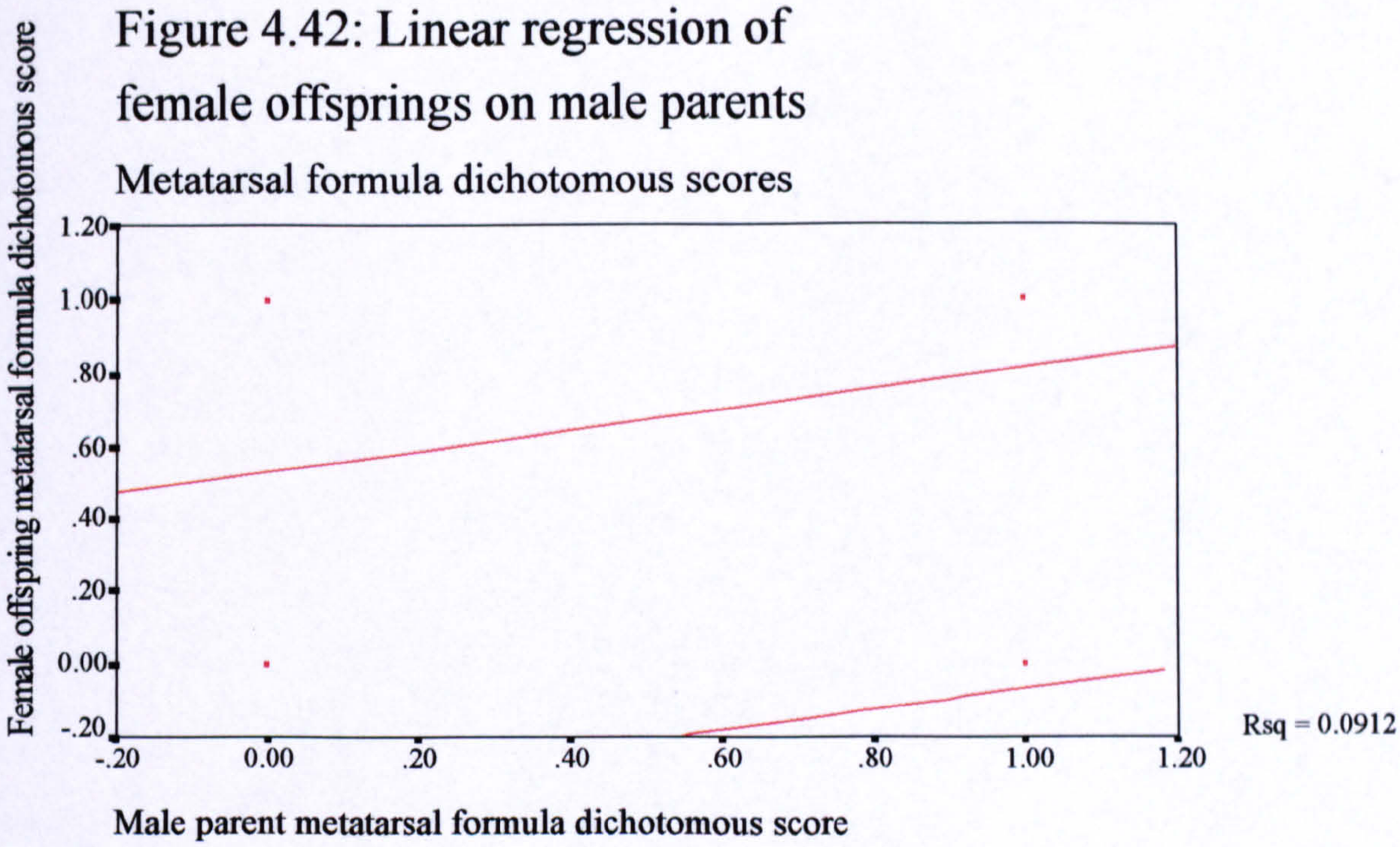


Figure 4.43: Linear regression of male offsprings on female parents

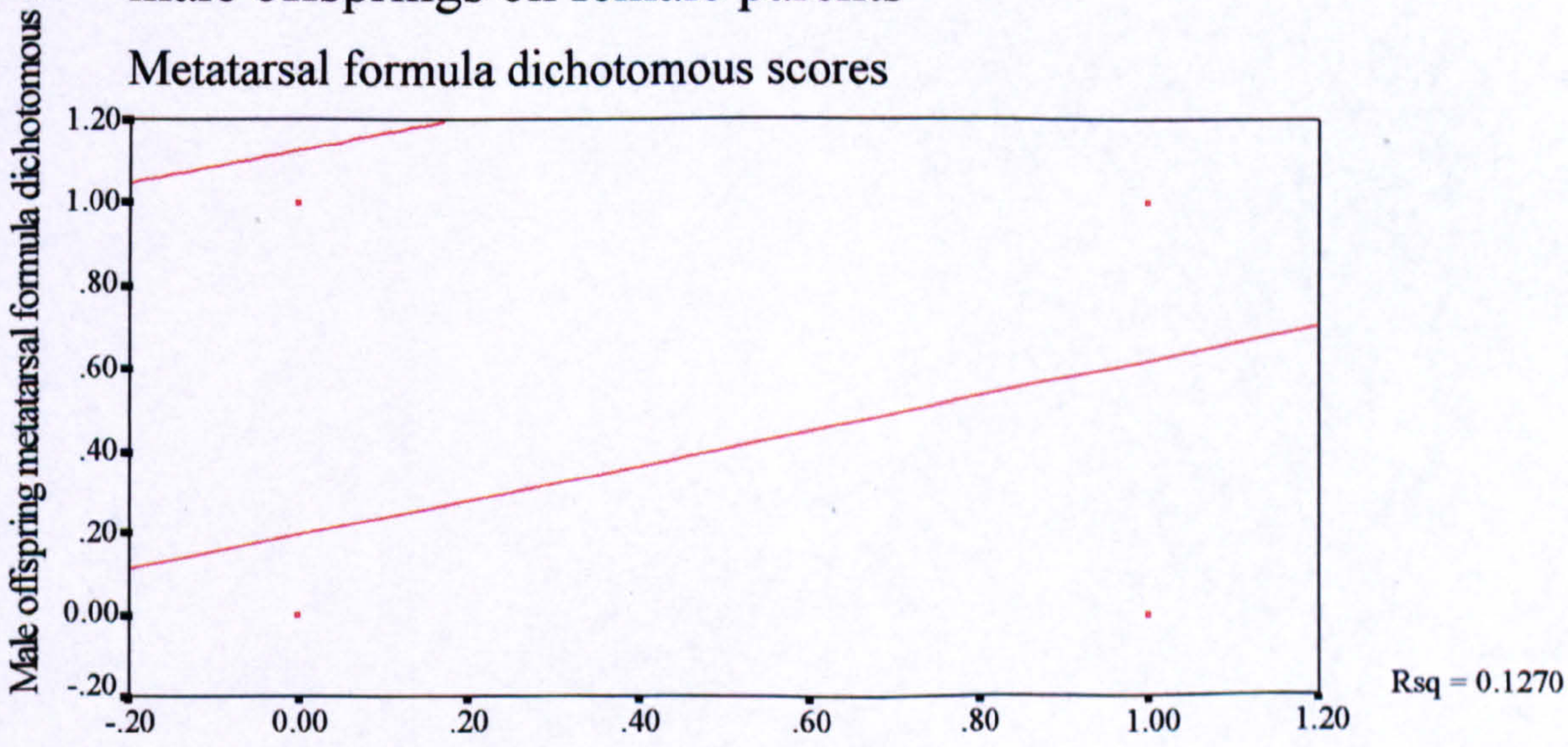


Figure 4.44: Linear regression of female offsprings on female parents

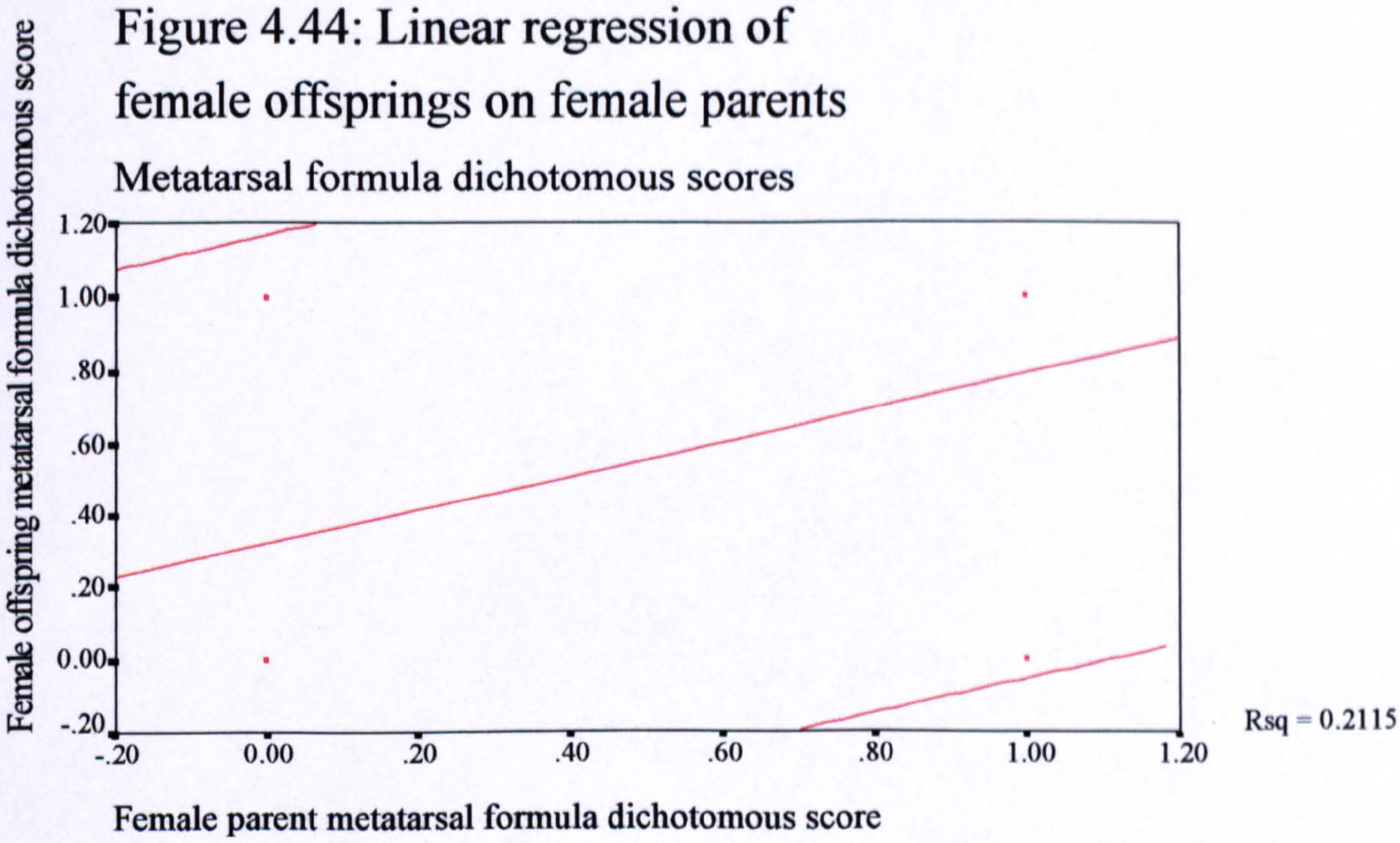


Figure 4.45: Linear regression of male offsprings on male parents

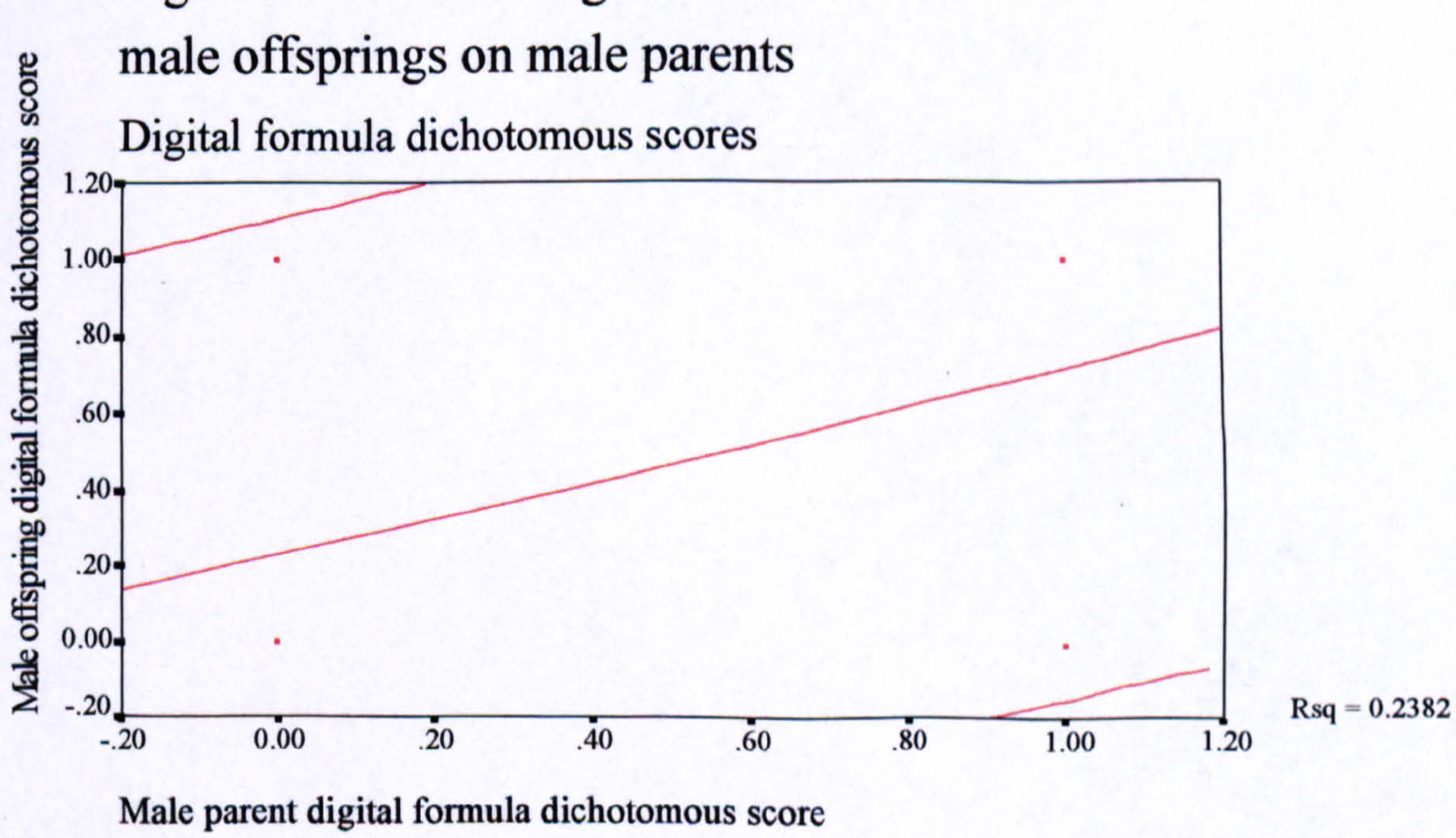


Figure 4.46: Linear regression of female offsprings on male parents

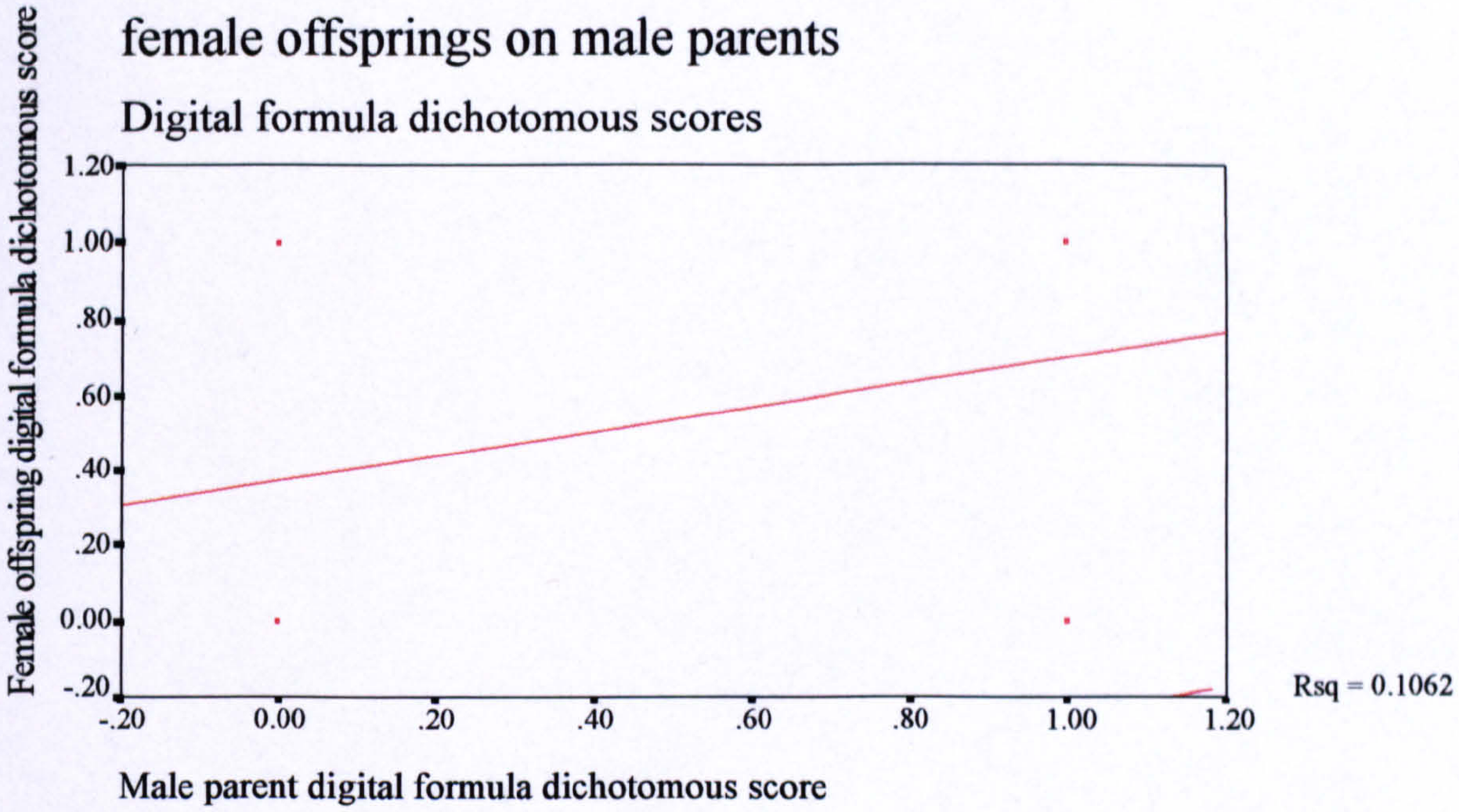


Figure 4.47: Linear regression of male offsprings on female parents

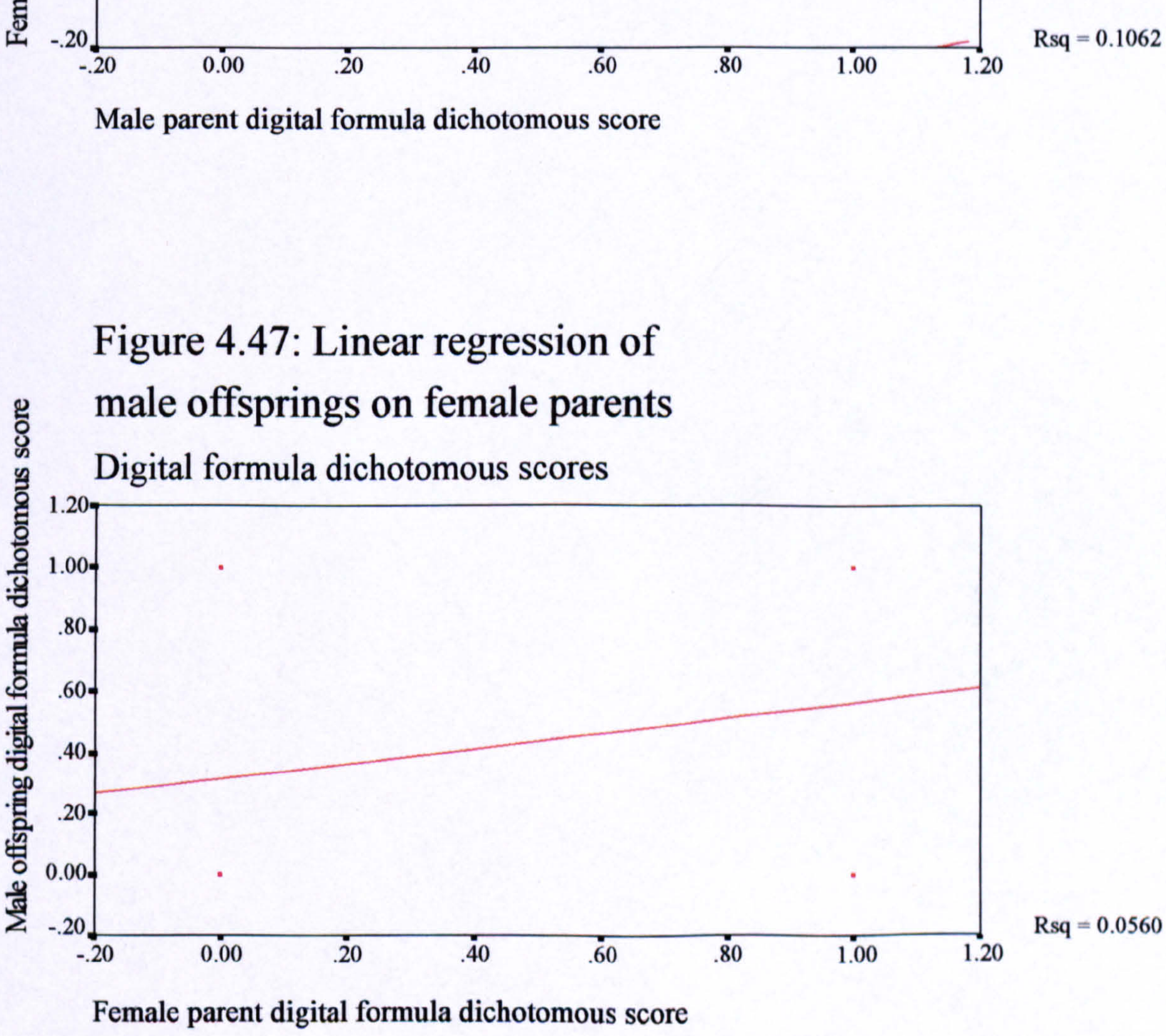
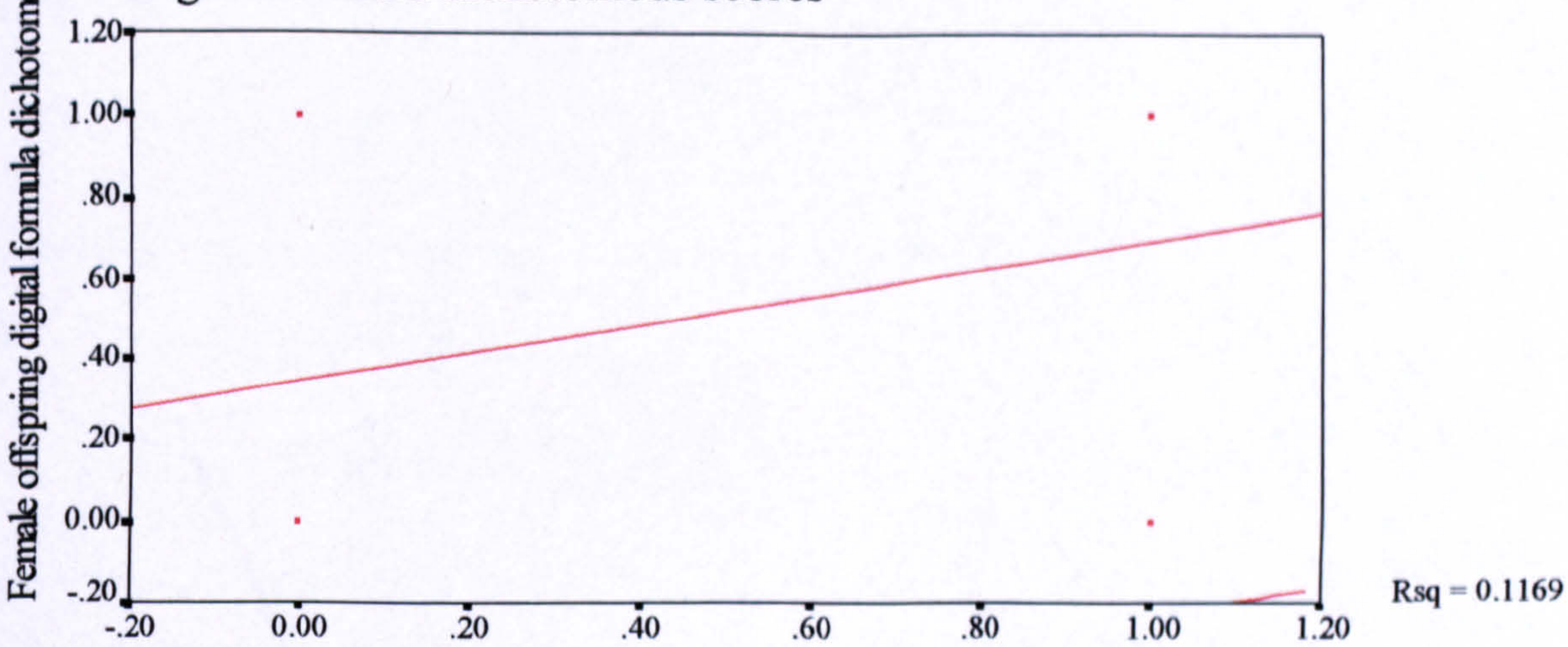


Figure 4.48: Linear regression of female offsprings on female parents



Data from the linear regression procedures was used to calculate the narrow sense heritability for the foot measurements. It was shown in Equation 3.20 that the slope of the linear regression line of offspring on parent values is equal to half the heritability estimate. The standard error of the regressions were therefore also equal to half of the standard error of the heritability estimates. Heritability was calculated separately for each gender. The heritability in males, for example, was estimated from the regression of male offspring on male parents and female offspring on male parents. The regression of female offspring on male parents must be adjusted for the difference in variance between genders. This was achieved by multiplying the heritability estimate by the ratio of the standard deviations of the foot measurements (e.g. arch index)of males to females. Thus,

(Equation 4.4)

$B' = B$ (S.D. male / S.D. female)

Where:

B'= gender adjusted regression

B = regression of female offspring on male parents

S.D. = standard deviation

Similarly, the heritability in females is estimated from the regression of female offspring on female parents and male offspring on female parents adjusted by:

(Equation 4.5)

B' = B (S.D. female / S.D. male)

Tables 4.8 -4.12 report the heritability estimates for the foot measurement data and their standard errors, with the adjustment factors.

Table 4.8 Heritability estimates for first metatarsophalangeal joint angle with standard error and gender adjustment factors.

Offspring Parent Regression	1st MPJ angle	
	Male Parent	Female Parent
Age Adjusted Male Offspring	.763796 ± .08261	.60695 ± .06769 x 1.1214188 = .6806451 ± .0759088
Age Adjusted Female Offspring	.501344 ± .088154 x .8917274 = .4470621 ± .0786093	.882928 ± .076736

Table 4.9 Heritability estimates for arch height index with standard error and gender adjustment factors.

Offspring Parent Regression	Arch height index	
	Male Parent	Female Parent
Age Adjusted Male Offspring	.438864 ± .09645	.100882 ± .056406 x 1.6 = .1614112 ± .0902496
Age Adjusted Female Offspring	.408454 ± .124756 x .625 = .2552837 ± .0779725	.44727 ± .061128

Table 4.10 Heritability estimates for first neutral position with standard error and gender adjustment factors.

Offspring Parent Regression	1st ray position	
	Male Parent	Female Parent
Male Offspring	.461918 ± .139168	.476962 ± .112948 x 1.0508475 = .5012143 ± .1186911
Female Offspring	.42145 ± .128274 x .9516129 = .4010572 ± .1220671	.525544 ± .101036

Table 4.11 Heritability estimates for metatarsal formula dichotomous score with standard error and gender adjustment factors.

Offspring Parent Regression	metatarsal formula	
	Male Parent	Female Parent
Male Offspring	.714286 ± .152112	.831688 ± .137924 x .94 = .7817867 ± .1296485
Female Offspring	.564368 ± .116496 x 1.0638298 = .6003914 ± .1239319	.942162 ± .10298

Table 4.12 Heritability estimates for digital formula dichotomous score with standard error and gender adjustment factors.

Offspring Parent Regression	digital formula	
	Male Parent	Female Parent
Male Offspring	.975506 ± .140572	.487918 ± .126242 x .94 = .4586429 ± .1186674
Female Offspring	.655754 ± .124604 x 1.0638298 = .6976106 ± .1325574	.700854 ± .10943

By taking averages of the male offspring on male parent and female offspring on male parent heritability estimates and their standard errors presented in Tables 4.8-4.12, averaged male heritability estimates for each of the foot measurement parameters can be calculated. Similarly, by taking averages of the male offspring on female parent and female offspring on female parent heritability estimates and their standard errors, averaged female heritability estimates for each of the foot measurement parameters can be calculated. Table 4.13 presents a summary of these final averaged male and female heritability estimates for the foot measurement parameters:

Table 4.13: Final, averaged heritability estimates for foot measurement parameters in males and females

PARAMETER	HERITABILITY MALES	HERITABILITY FEMALES
1st MPJ angle	0.61 ± 0.08	0.78 ± 0.08
AHI	0.35 ± 0.09	0.30 ± 0.08
1st RNP	0.43 ± 0.13	0.51 ± 0.11
Metatarsal formula	0.66 ± 0.14	0.86 ± 0.12
Digital formula	0.84 ± 0.14	0.56 ± 0.11

Since the percentages of genetic and environmental factors influencing 1st MPJ angle, arch height index, first ray neutral position, metatarsal formula and digital formula within the sample are given by the estimation of heritability, the calculation of heritability estimates in males and females for the variables allows refinement of the model proposed in Section 3.1 (Equation 3.1). Two refinements to the model are possible, one for each gender, if the heritabilities of the variables are calculated for males and females. These refined models are expressed in equations 4.6 and 4.7 for males and females respectively.

(Equation 4.6)

Males: $(1^{st}\ \text{MPJ angle}_{G=0.61}+1^{st}\ \text{MPJ angle}_{E=0.39}) = f(\text{AHI}_{G=0.35}+\text{AHI}_{E=0.65}), (\text{MF}_{G=0.66}+\text{MF}_{E=0.34}),$ $(\text{DF}_{G=0.84}+\text{DF}_{E=0.16}), (\text{FRNP}_{G=0.43}+\text{FRNP}_{E=0.57}), (O_G + O_E), S, A$

(Equation 4.7)

Females: $(1^{st}\ \text{MPJ angle}_{G=0.78} + 1^{st}\ \text{MPJ angle}_{E=0.22}) = f(\text{AHI}_{G=0.30}+\text{AHI}_{E=0.70}), (\text{MF}_{G=0.86}+\text{MF}_{E=0.14}),$ $(\text{DF}_{G=0.56}+\text{DF}_{E=0.44}), (\text{FRNP}_{G=0.51}+\text{FRNP}_{E=0.49}), (O_G + O_E), S, A$

Where:
$_G$= Genotype
$_E$= Environment (all non-genetic factors)
AHI= Arch height index
MF= Metatarsal formula
DF= Digital formula
FRNP =First ray neutral position
O= Other known and unknown factors
S= Gender
A= Age

Although these refinements to the model provide an understanding of the relative importance of genetic and environmental influences in the ontogeny of the foot characteristics, they allow no understanding of the interaction of these variables or of their relative importance in determining 1st MPJ angle and, thus, hallux valgus. In order to shed light on the interactions between the variables, further analyses of data and refinement of the model was necessary.

PART II

4.7 Predictive Model Building

To provide an understanding of the interaction of the variables and to evaluate their relative importance in determining 1st MPJ angle the model proposed in Section 3.1 and refined in Section 4.6 required further refinement to mathematical form. Multiple regression analysis provides an assessment of the relationship between a dependent variable and several independent variables, allowing this refinement.

1st MPJ angle represented the dependent variable, since the desired outcome of the analysis was a model which allows the prediction of 1st MPJ angle from the other variables. The remaining variables- age, gender, arch height index, first ray neutral position, metatarsal formula and digital formula- were the independent variables. In addition to these variables, the results of the heritability analyses (Section 4.6) revealed that genetic influences were significant in the determination of 1st MPJ angle (Table 4.13). A family history of hallux valgus, therefore, appears significant as an aetiological factor and should be taken into account in the predictive model. Inclusion within the model of a variable containing family history may provide further delineation of the factors influencing 1st MPJ angle, a better understanding of the aetiology of hallux valgus and a stronger model for the prediction of 1st MPJ angle. Family history was represented using a dichotomous variable. If two or more individuals from a given family group had 1st MPJ angle $\geq 15^0$, all members of the family were awarded a score of 1, indicating a positive family history for abnormally high 1st MPJ angles, or hallux valgus. If only one member of a family group had a 1st MPJ angle $\geq 15^0$, all members of the family were awarded a score of 0, indicating no family history.

Not all available data was used to build the multiple regression model. It was necessary to hold back some of the data to test the ability of the model to predict 1st MPJ angle and, thus, hallux valgus, once built. Furthermore, by building the model with data from related individuals the model may have lacked validity in the prediction of hallux valgus in a population of unrelated individuals since genetic influences have been shown to be significant in the determination of 1st MPJ angle and are accounted for in the model anyway. A subset of data that would overcome this was created from the sample to

build the model. One individual from each family group was selected. Graphical representation of the data of this sample are given in Figures 4.49-4.56.

Figure 4.49: Distribution of age data model building sample

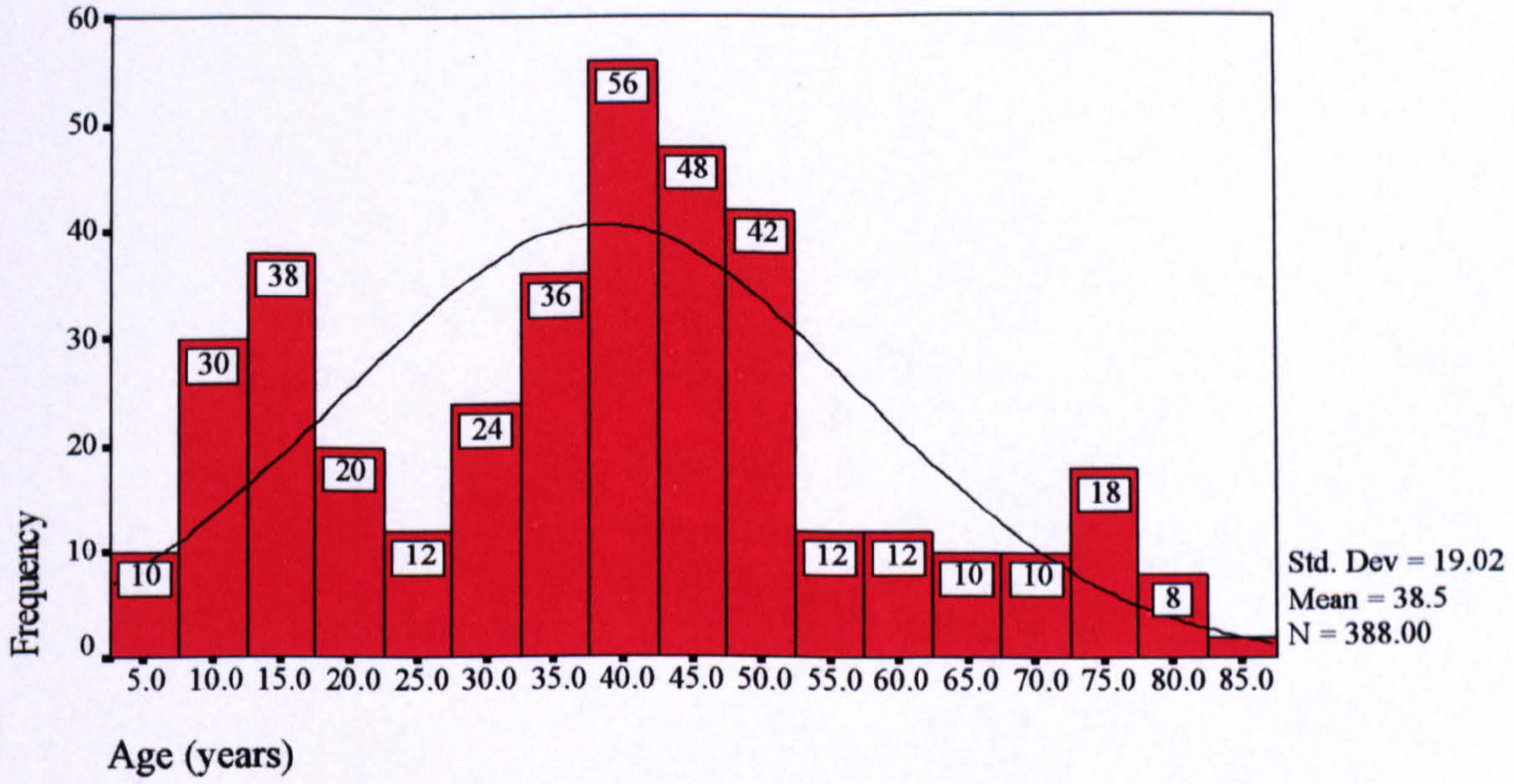


Figure 4.50: Distribution of gender data model building sample

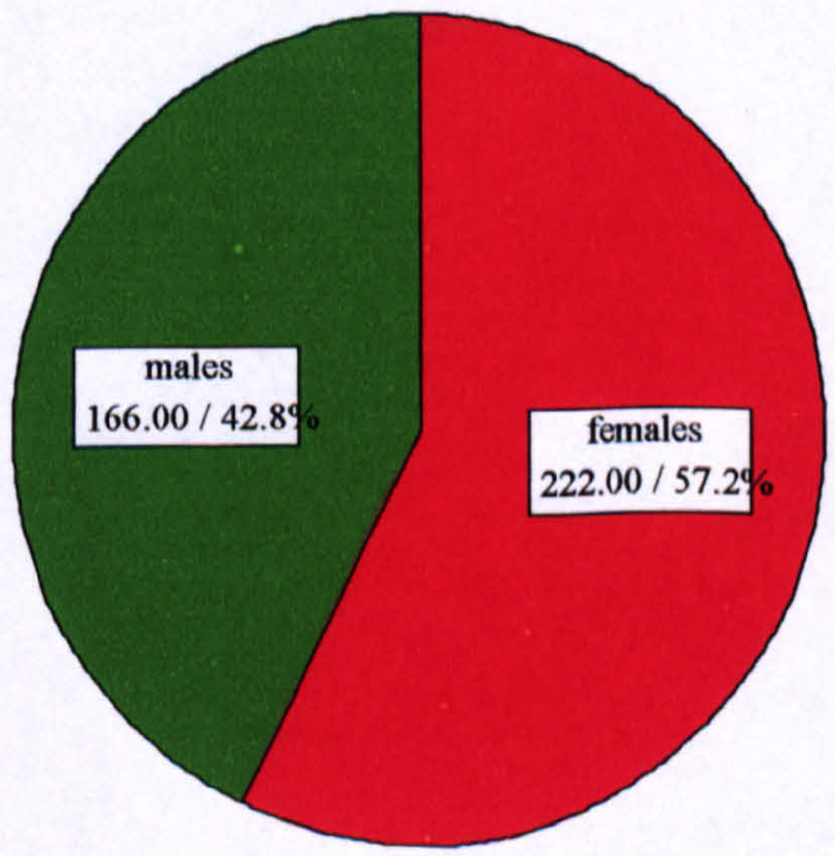


Figure 4.51: Distribution of 1st MPJ angle data model building sample

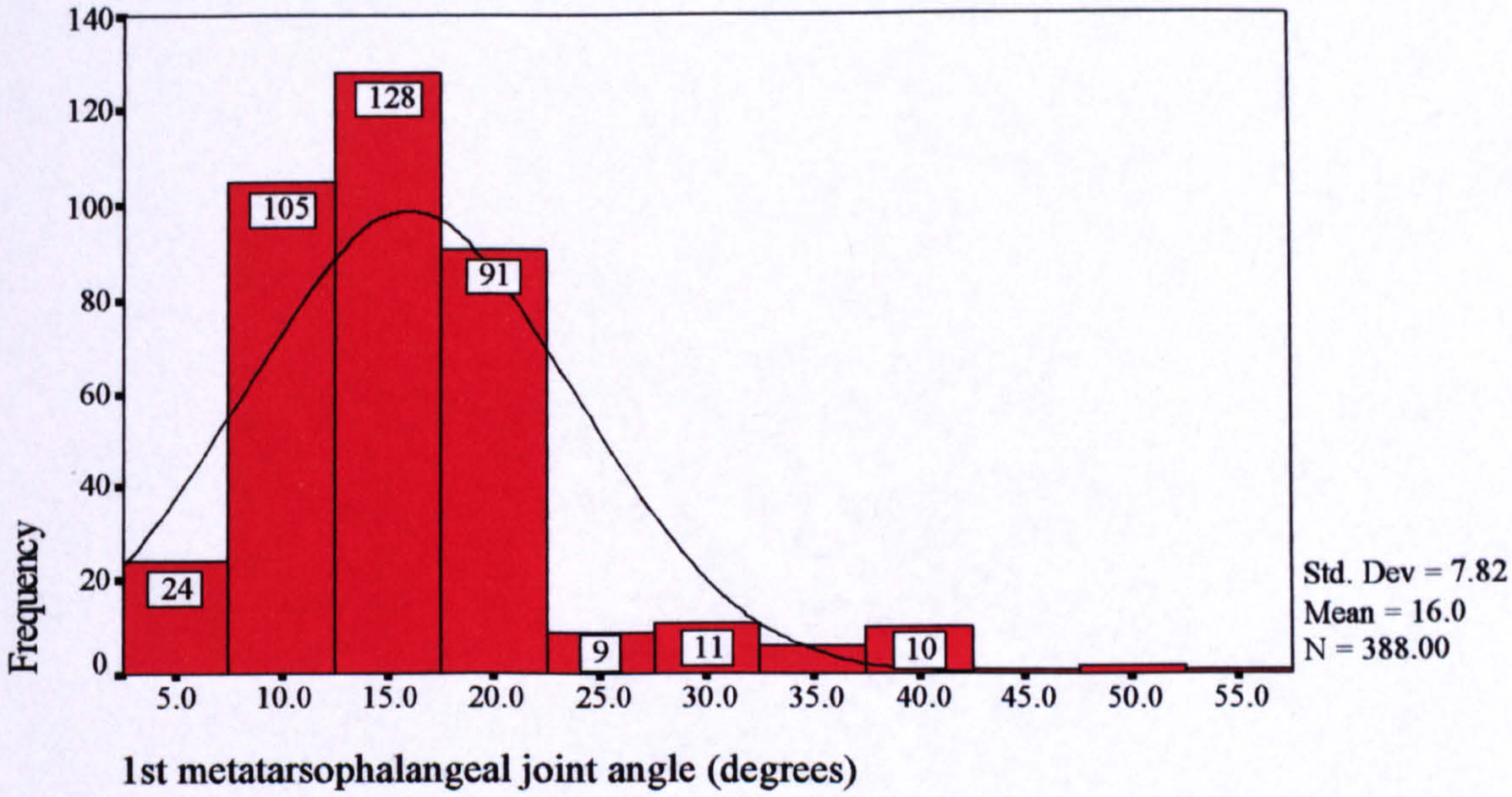


Figure 4.52: Distribution of arch height index data model building sample

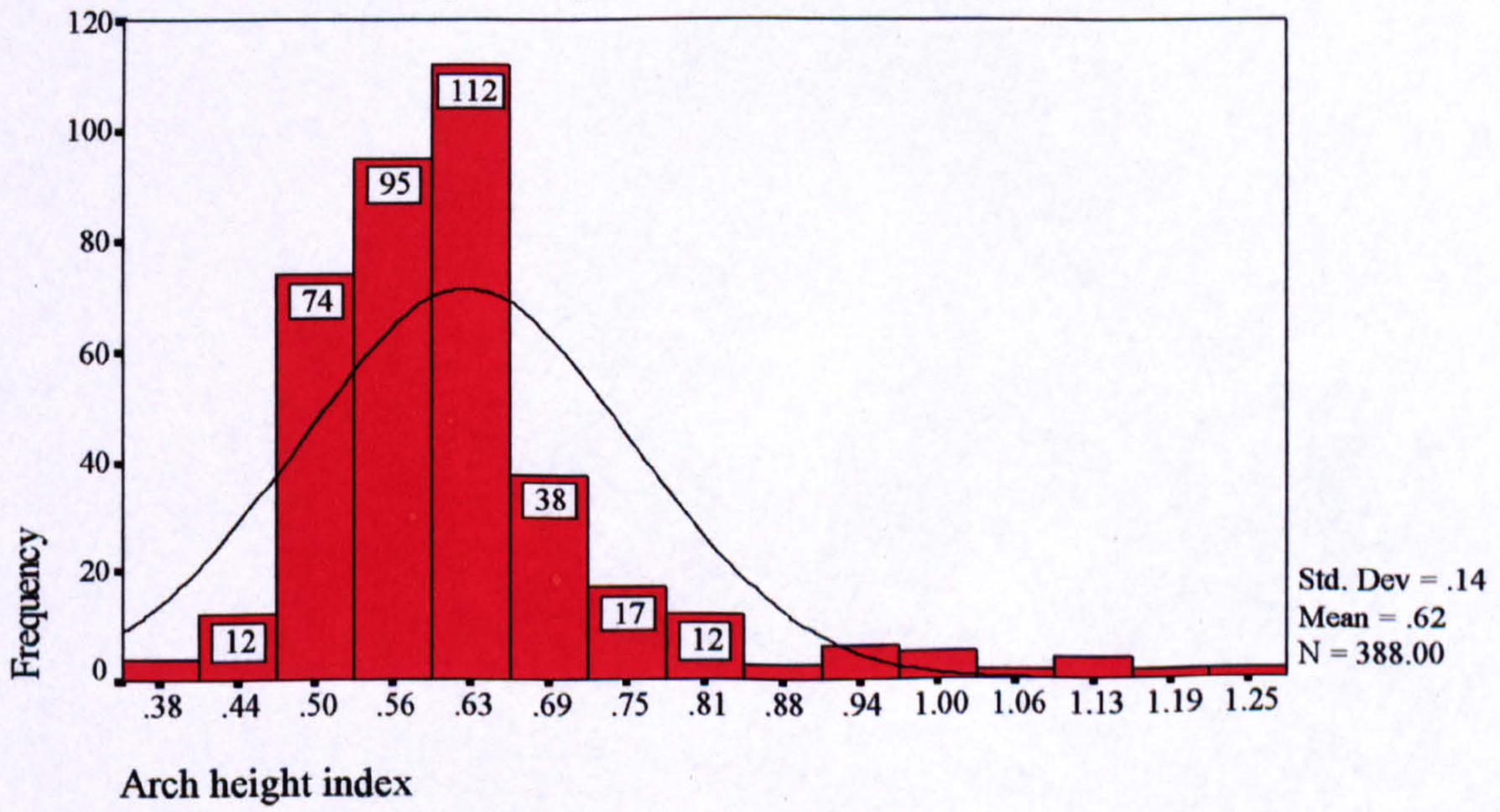


Figure 4.53: Distribution of 1st ray neutral position data model building sample

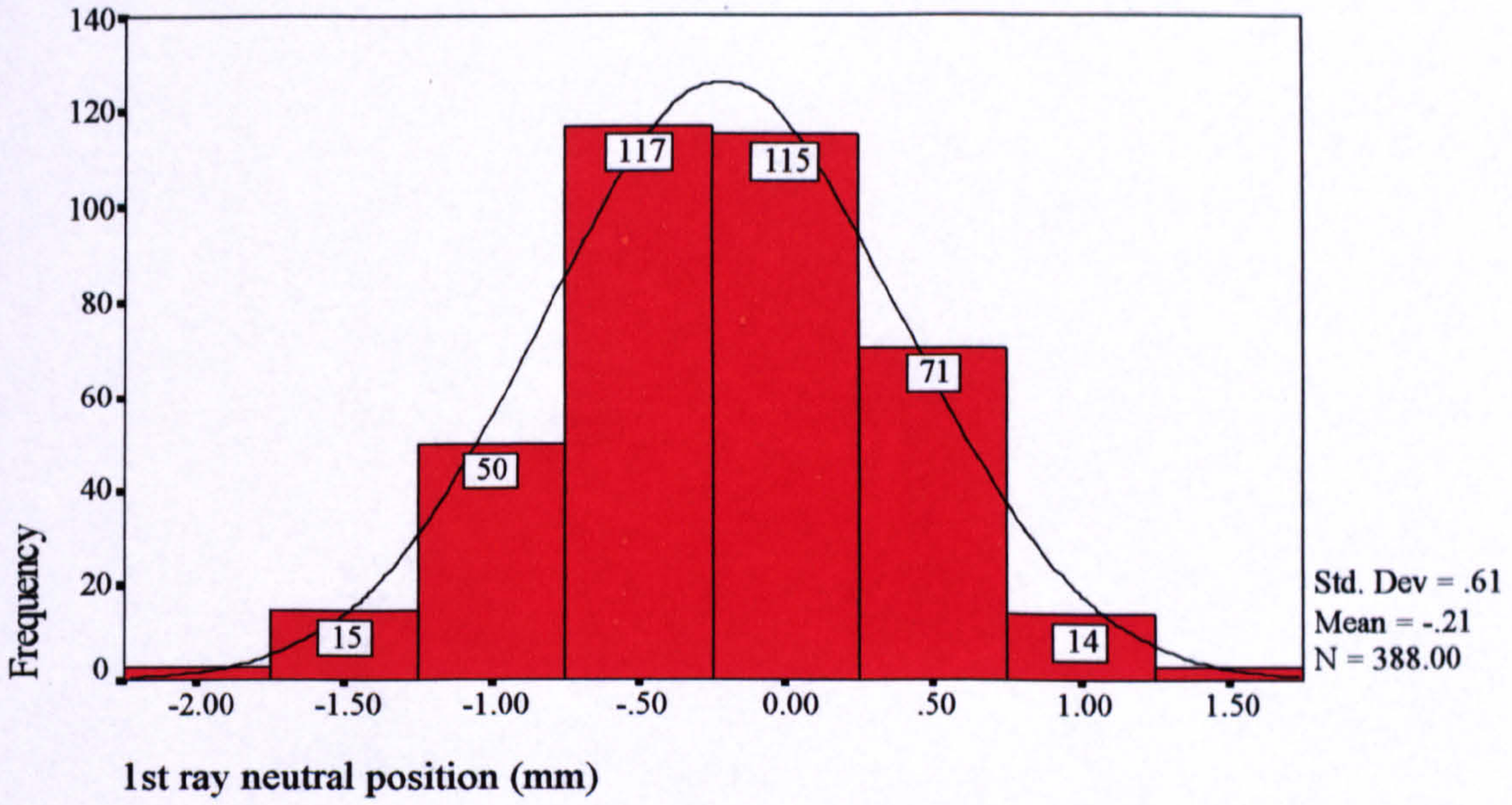


Figure 4.54: Distribution of metatarsal formula score data model building sample

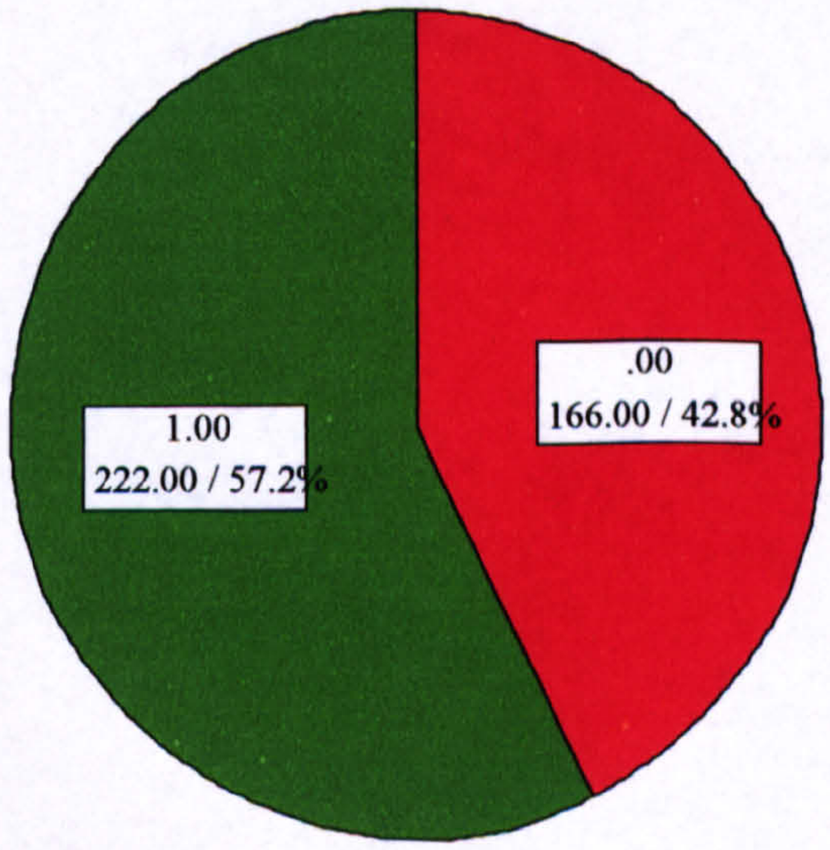


Figure 4.55: Distribution of digital formula score data model building sample

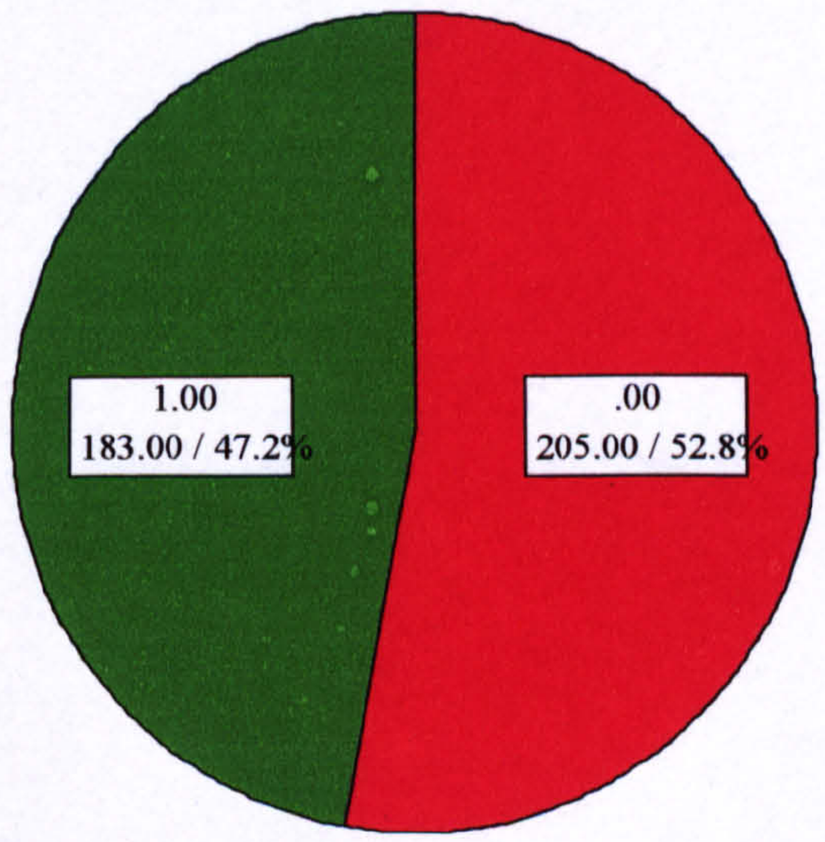
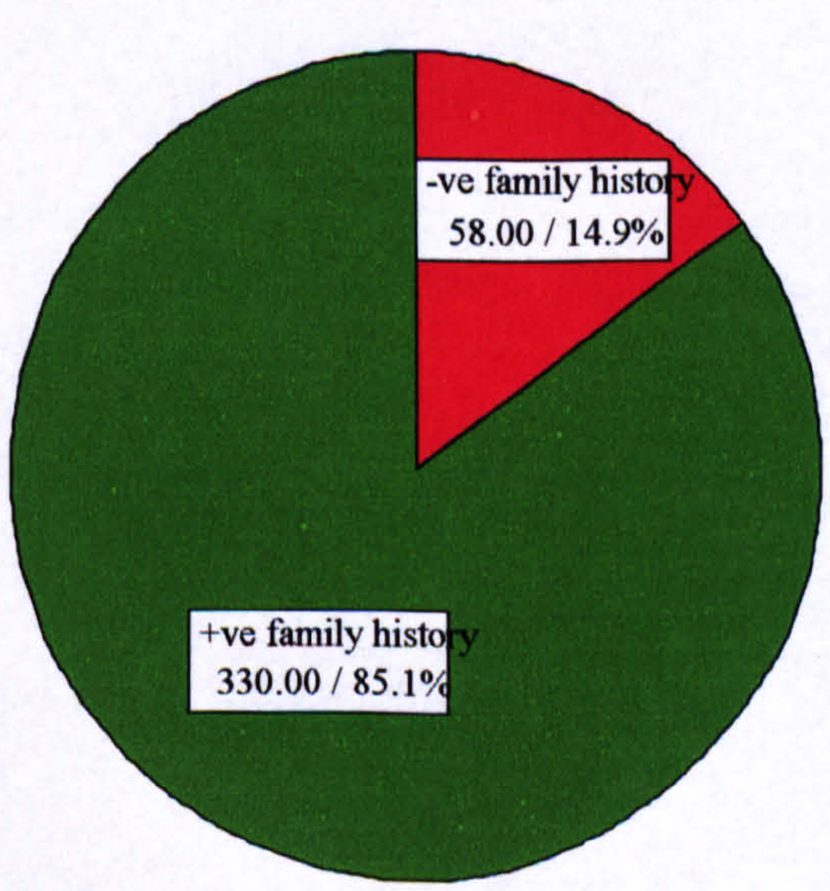


Figure 4.56: Distribution of family history data model building sample



Multiple regression can be used when independent variables are correlated. However, since the regression equation is linear, curvilinear relationships may require linear transformation prior to analysis (Norusis 1993). Thus, prior to modelling, knowledge of the inter-relationships between the variables was sought. Inter-relationship models were developed using the curve-fit procedure. The full results of this procedure are provided in Appendix 4.

Examination of r^2 values revealed that in all cases the linear models described the inter-relationships between variables adequately; no significant increase in r^2 (increase < 0.1) occurred with the addition of coefficients and consequential loss of degrees of freedom offered by the quadratic and cubic models. Based on this evidence, none of the variables required linear transformation prior to modelling and the use of multiple linear regression appeared valid.

Forward selection for the multiple linear regression procedure was used. In forward selection the first variable considered for entry into the equation is the independent variable with the largest positive or negative correlation with the dependent variable. The procedure was terminated when there are were no further variables. Thus, the first independent variable entered is always the best predictor of the dependent variable followed by a list of other predictors in decreasing order of importance (Norusis 1993).

In section 4.6 separate analyses were performed for male and female data and consequently two refinements of the model were presented (Equations 4.6, 4.7). Separation of male and female data was necessary for the estimation of heritability since differences existed in the variances of male and female foot parameters. However, for the purpose of predictive model building, male and female data could be pooled since a dichotomous variable representing gender was included as an independent variable: thus, the effects of gender are accounted for within the model.

Table 4.14 gives summary and analysis of variance statistics for the multiple linear regression model.

Table 4.14: Summary and analysis of variance statistics; multiple linear regression model.

Dependent Variable	1st MPJ Angle				Linear Regression
Step	MultR	R^2	T	SigT	
1 Arch index	.63580	.40425	9.767	.0000	
2 Age	.73542	.54085	11.583	.0000	
3 Metatarsal formula	.77131	.59491	3.437	.0002	
4 Gender	.78557	.61713	-4.921	.0000	
5 1st ray position	.79599	.63360	-3.987	.0001	
6 Family history	.80451	.64724	3.735	.0002	
7 Digital formula	.80493	.64792	.858	.3916	
Adjusted R^2	.64792				
Standard Error	4.68286				

Analysis of Variance			
	DF	Sum of Squares	Mean Square
Regression	7	15334.91247	2190.7018
Residuals	380	8333.07722	21.9292
F= 99.89907	Significance of F= .0000		

	Variables in the Equation			
Variable	B	SE B	95% confidence interval B	Beta
Age	.164446	.014197	.136532, .192359	.399996
Arch Index	20.054341	2.053285	16.017118, 24.091564	.347265
Gender	-2.514501	.511002	-3.519248, -1.509755	-.159289
Family history	2.658623	.711754	1.259154, 4.058092	.121376
Metatarsal formula	2.027354	.589864	.867548, 3.187159	.128429
1st ray position	-1.649915	.413790	-2.463521, -.836310	-.129473
Digital formula	.471998	.550351	-.610117, 1.554112	-.159289
Constant	-5.654119	1.287803	-8.186209, -3.122028	

The results of the multiple linear regression analysis allows refinement of the predictive model to linear regression form. This model is predictive for 1st MPJ angle and therefore may be used in the prediction of hallux valgus. The predictive linear regression model is expressed in equation 4.8.

(Equation 4.8)

1st MPJ angle = (AHI 20.054 ± 4.037)+(A 0.164 ± 0.0279)+(MF 2.027 ± 1.160)+(S -2.515 ± 1.005)+ (FRNP -1.650 ± 0.814)+(FH 2.659 ± 1.400)+(DF 0.472 ± 1.082)+ -5.654 ± 2.532

Where:
AHI =Arch height index
A =Age
MF =Metatarsal formula
S =Gender
FRNP =First ray neutral position
FH =Family history
DF =Digital formula

4.8 TESTING THE MODEL

To test the model a second subset of data was randomly generated from the original sample (individuals used for model building were disqualified from selection). Graphical representation of the data of this sample are given in Figures 4.57-4.64.

Figure 4.57: Distribution of age data model testing sample

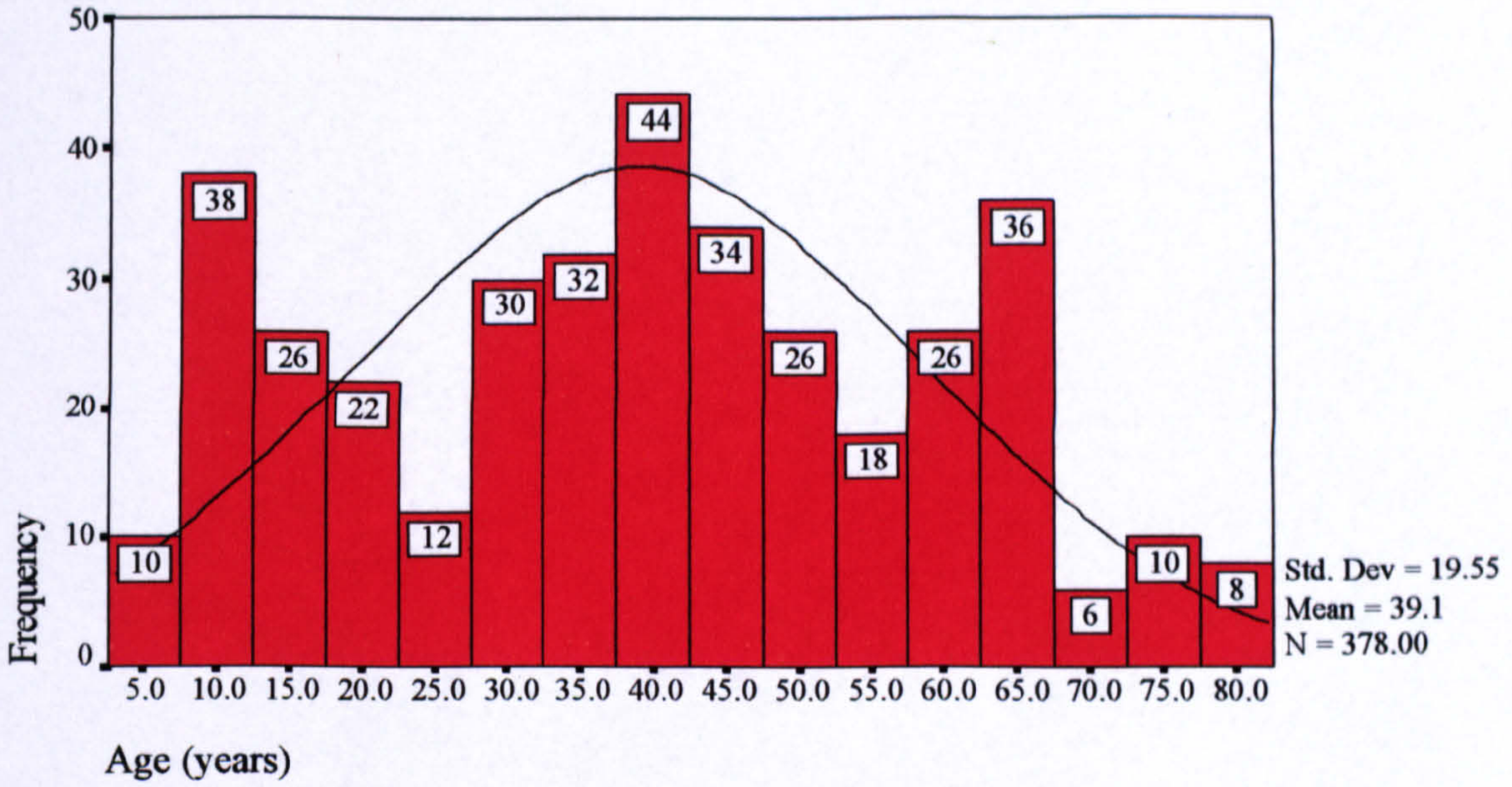


Figure 4.58: Distribution of gender model testing sample

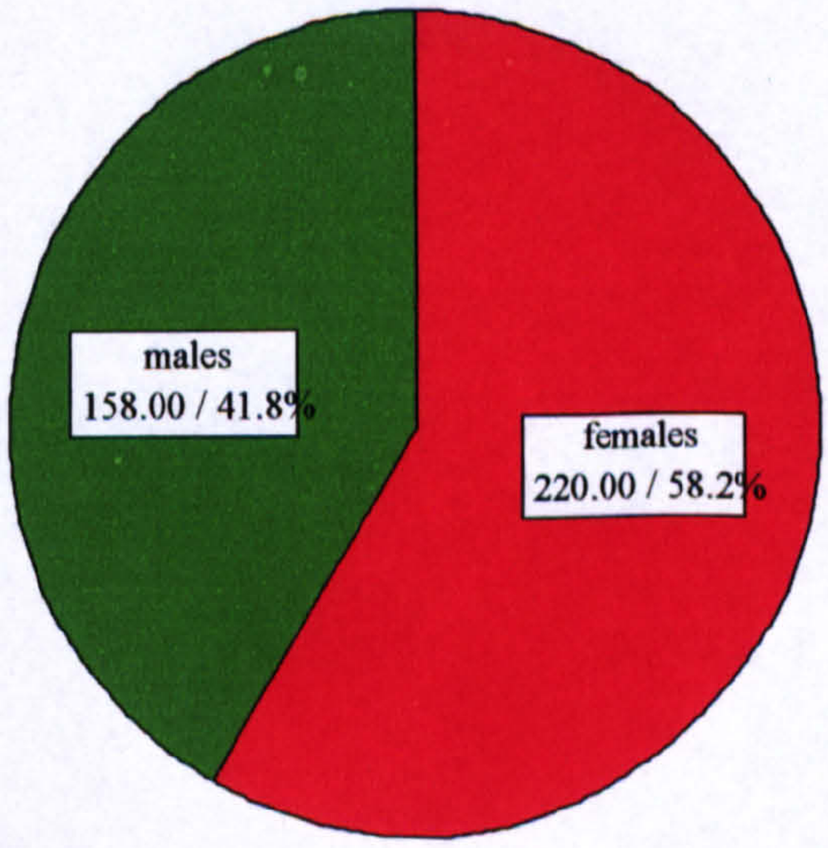


Figure 4.59: Distribution of 1st MPJ angle data model testing sample

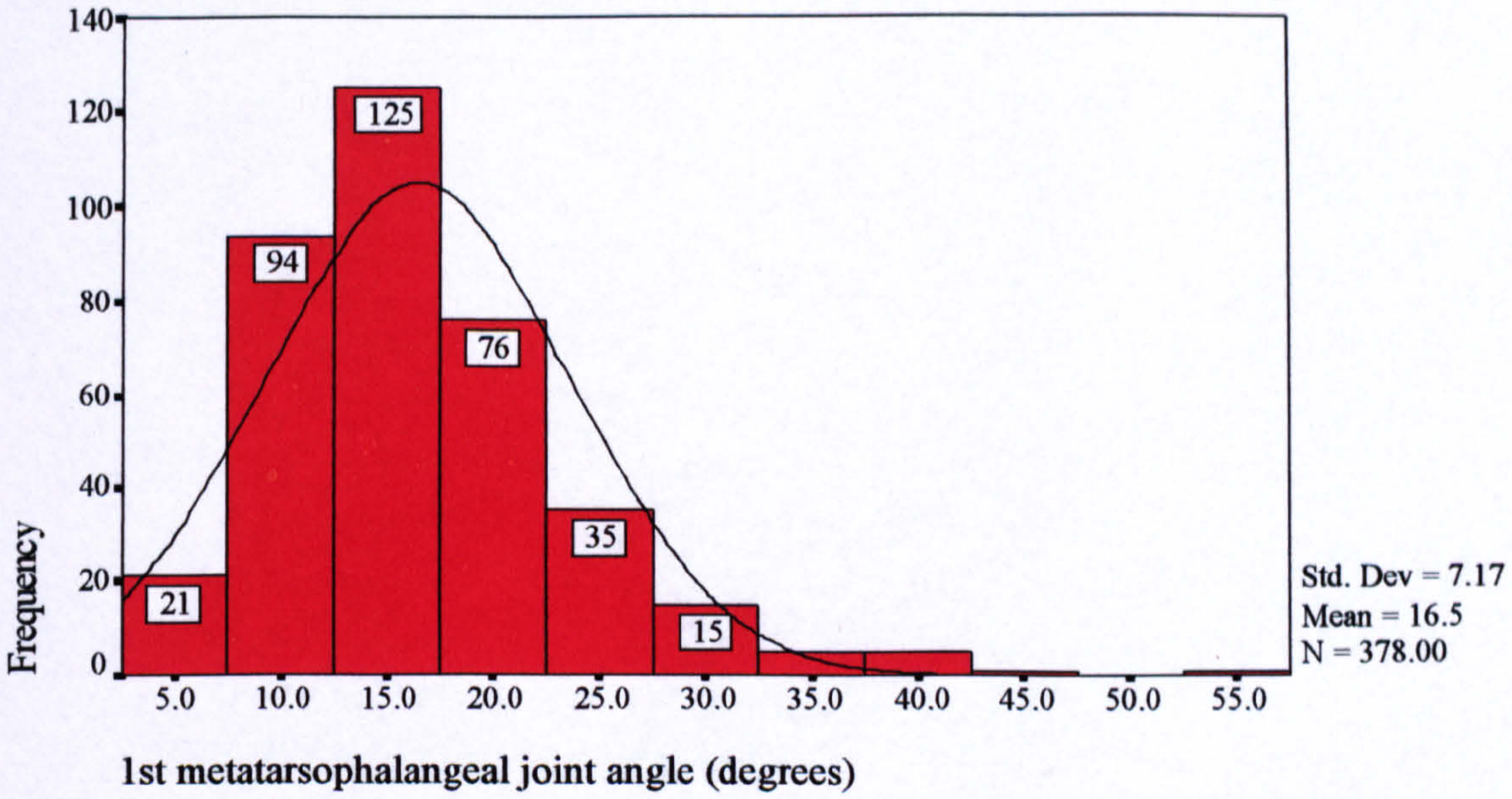


Figure 4.60: Distribution of arch height index data model testing sample

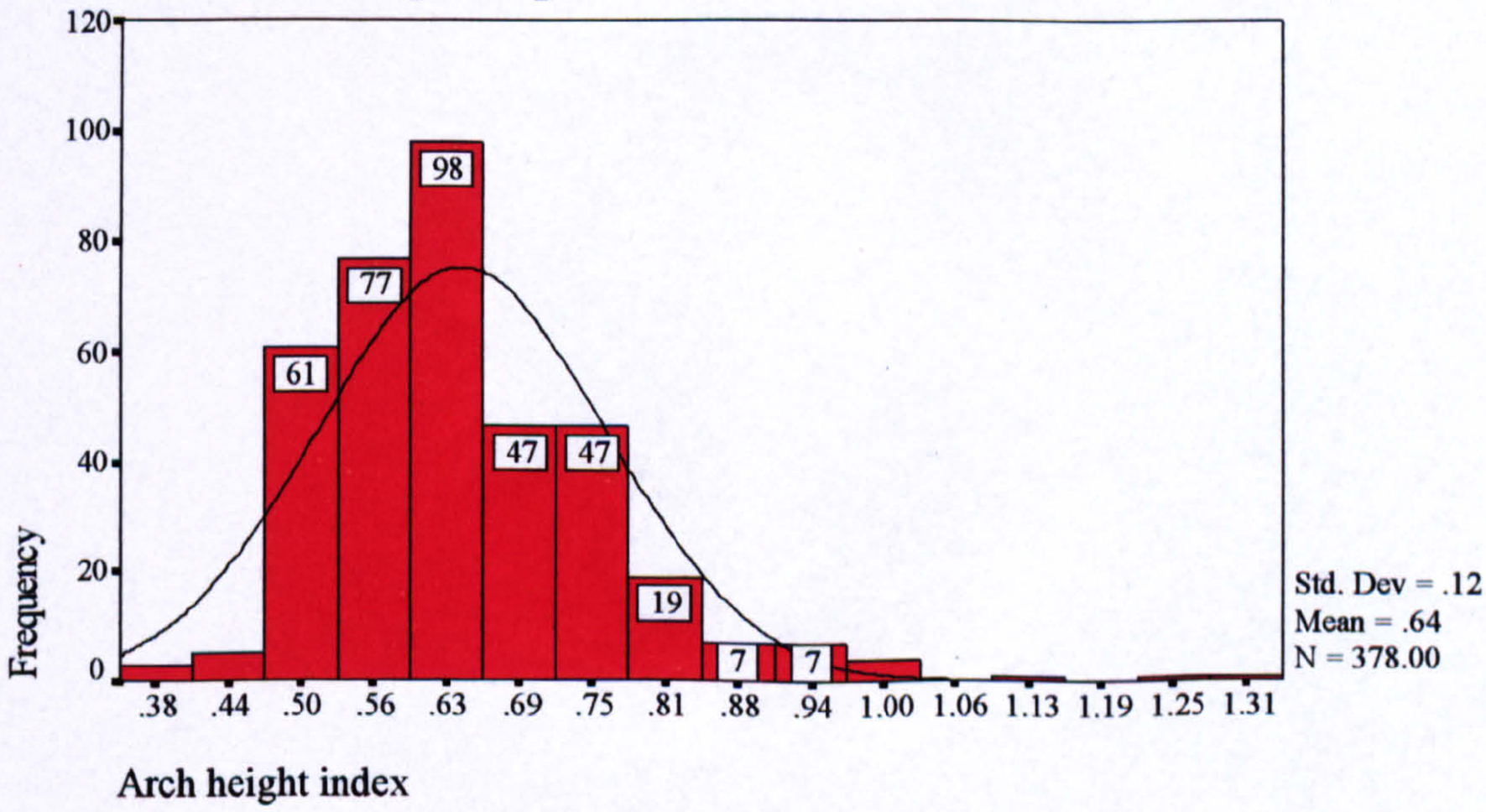


Figure 4.61: Distribution of 1st ray neutral position data model testing sample

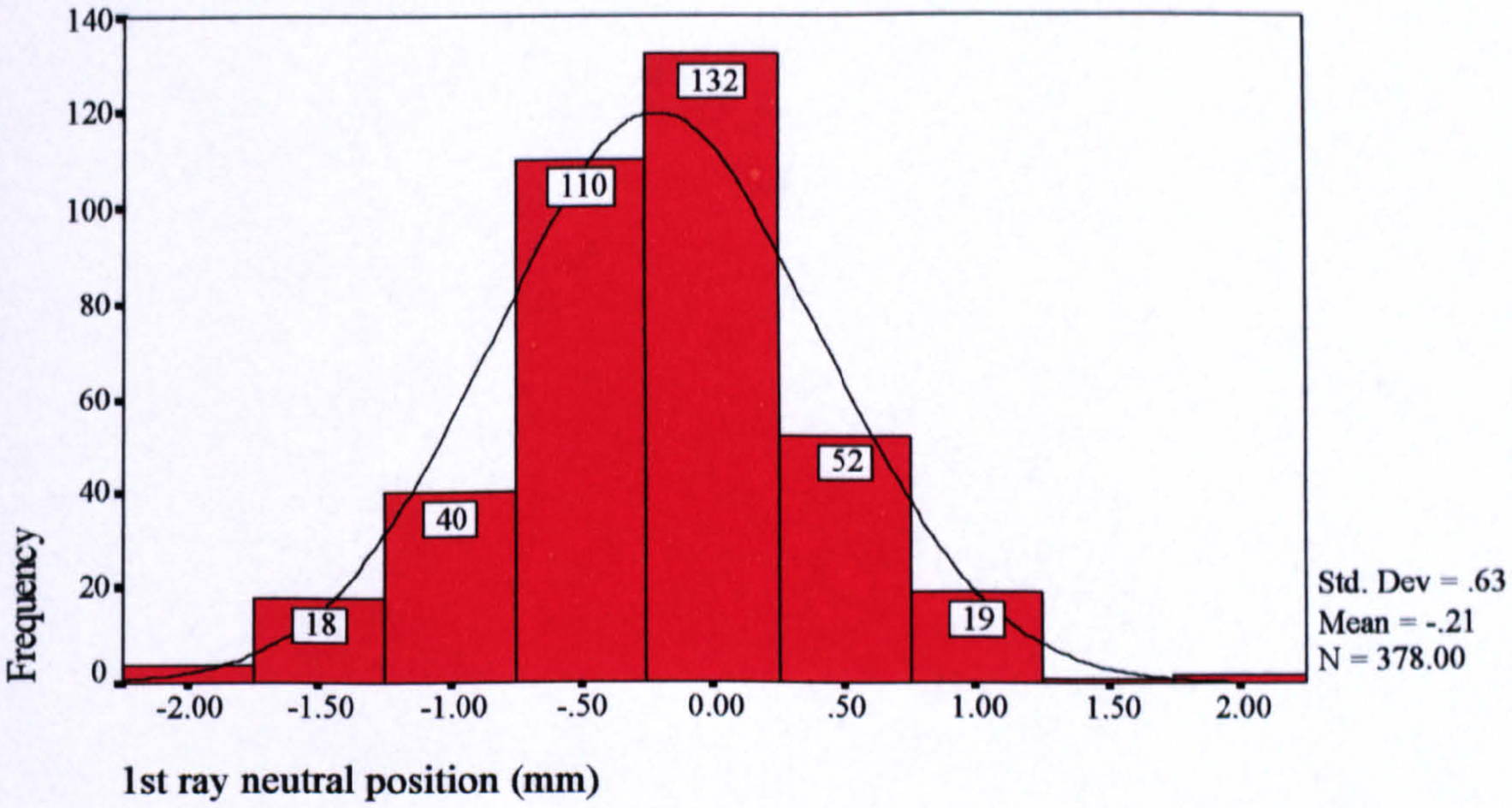


Figure 4.62: Distribution of metatarsal formula score data model testing sample

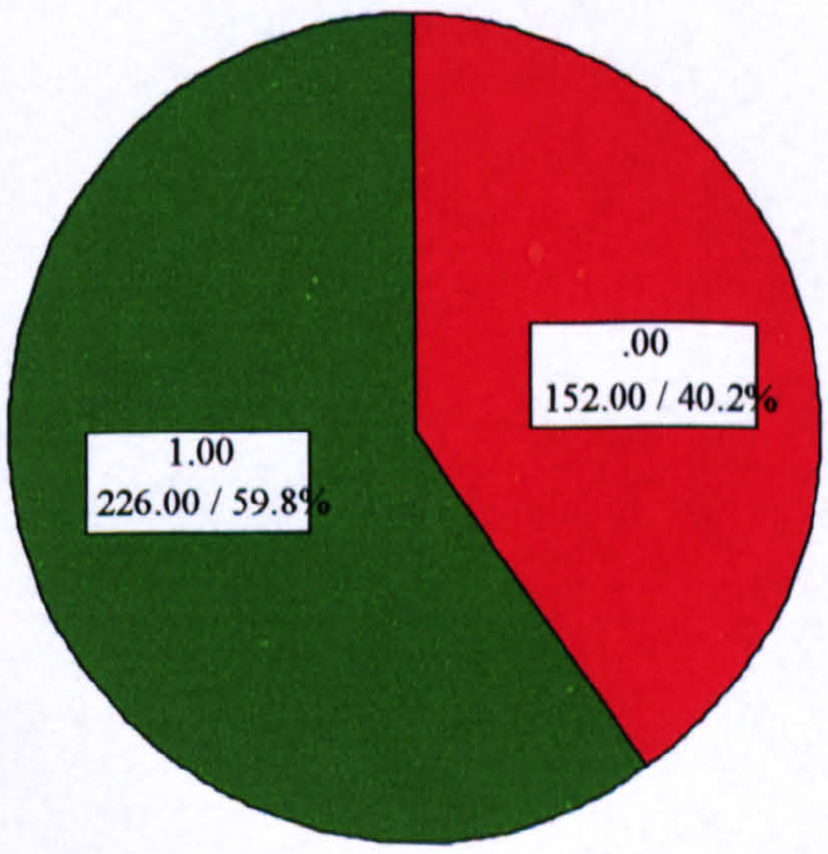


Figure 4.63: Distribution of digital formula score data model testing sample

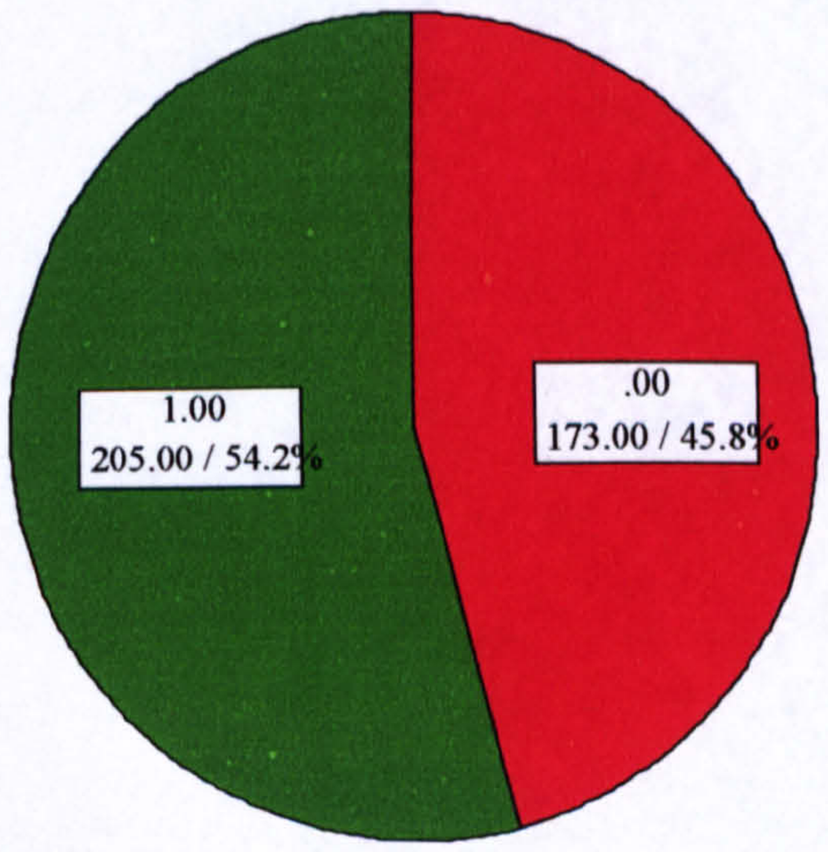
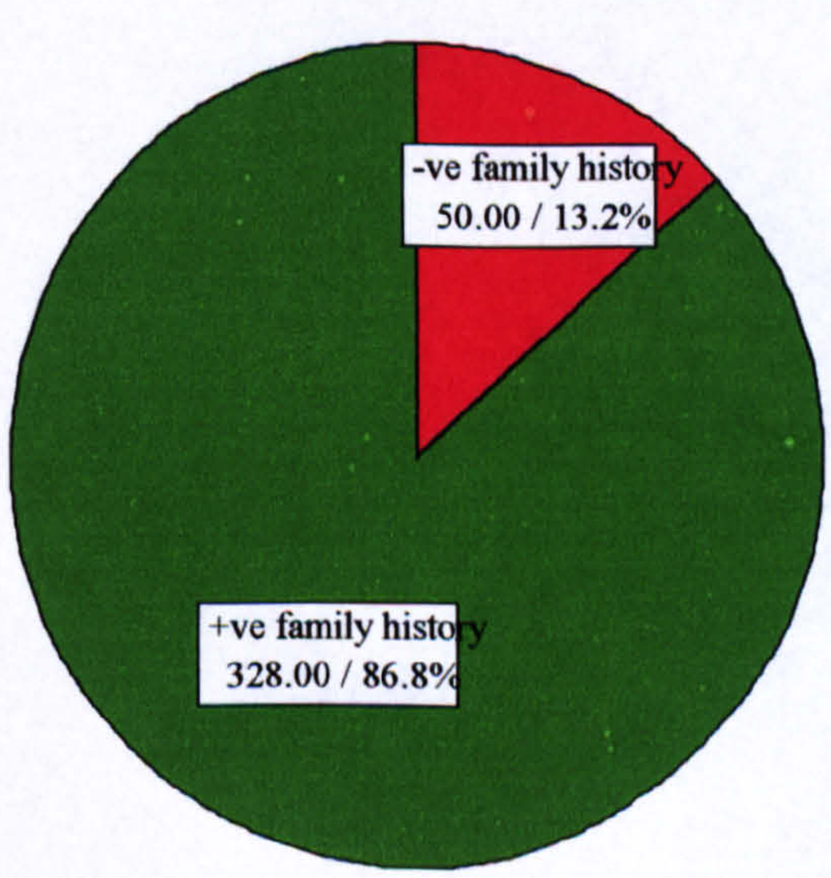


Figure 4.64: Distribution of family history data model testing sample



Running the data from the second subset through equation 4.8 yields the best estimate of 1st MPJ angles. A strong linear relationship should exist between these predicted values and the observed values if the model is a good predictor of 1st MPJ angle. This relationship is depicted graphically in Figure 4.65. The errors in the models estimates are represented graphically in Figure 4.66.

Figure 4.65: Linear regression of predicted 1st MPJ angles on 1st MPJ angles, measured using the Kilmartin finger goniomete

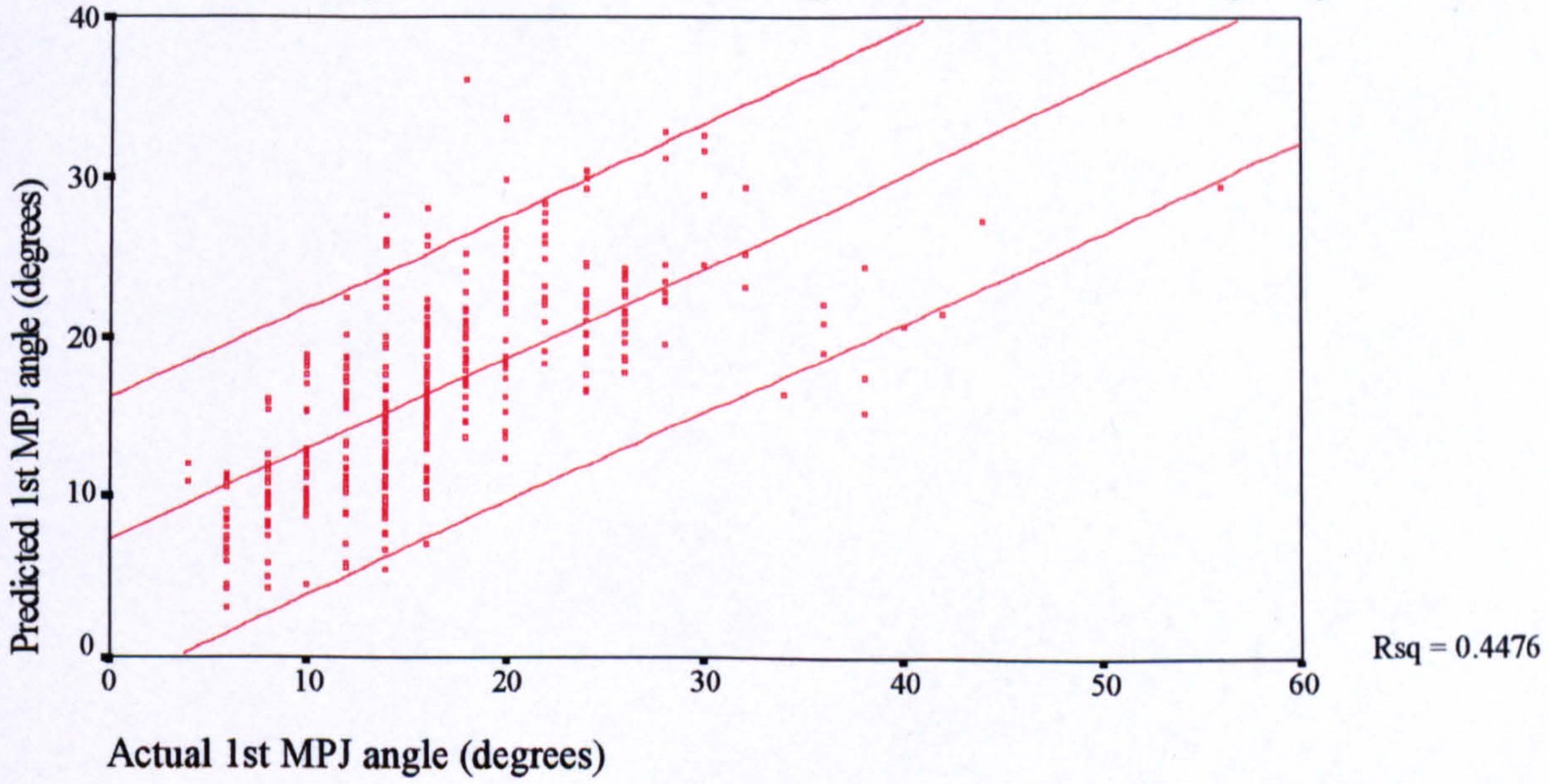
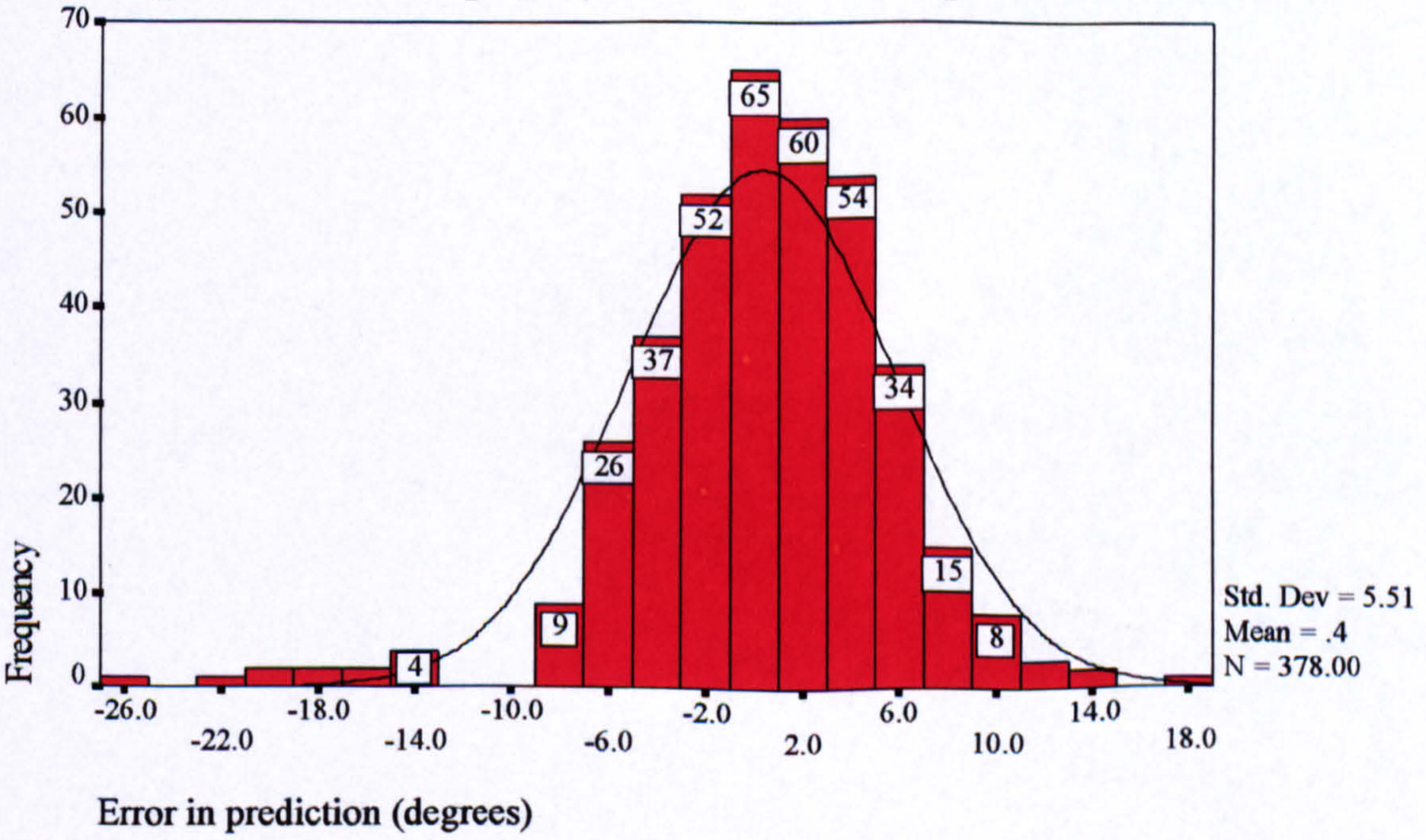


Figure 4.66: Frequency distribution of prediction errors



Running data from this second subset through Equations 4.8 at the upper and lower 95% confidence intervals provides upper and lower 95% confidence intervals for predicted 1st MPJ angles. The efficiency of the model may be tested by calculating how many individuals observed measurements fall within the 95% confidence limits of prediction.

It was found that 92.1% (n= 348) of the observed 1st MPJ angle measurements fell within the 95% confidence intervals predicted by the model (Figure 4.65). This efficiency appears excellent. The model provides an accurate method of prediction of 1st MPJ angle and, therefore, hallux valgus.

4.9 Application of the Model

The model developed within this study and presented in Section 4.7, provides the clinician, for the first time, with a method of identifying individuals at risk of developing hallux valgus. However, the 95% confidence limits associated with the prediction must be taken into consideration when the prediction is evaluated. Given that an artificial delineation of 15° is used to differentiate normality from abnormality, it is easy to see that often the 95% confidence limits of the prediction may span both the normal and abnormal ranges. In this situation, the probability (risk) of the individual developing hallux valgus can be determined.

For example, a prediction of 20° is obtained for the first metatarsophalangeal joint angle of an individual with 95% confidence limits of 10°, 30°. Given that the delineation between normality and abnormality in first metatarsophalangeal joint angle is set at 15°, approximately 75% of the 95% confidence interval range lies beyond the abnormal threshold and only 25% lies within the normal range. Thus, the probability that the individuals angle will be beyond the abnormal threshold is approximately 0.75. Therefore, there is a 75% risk that the individual will develop hallux valgus.

The model may also be used as a tool to simulate the progression of 1st MPJ angle with time.

For example, one of the individuals in the sample was a female age 20, who presented with a positive family history of hallux valgus. When assessments of the predictor variables were made using the methods described in Chapter III the following values for the variables were obtained:

Arch height index=0.4
Age=20
Metatarsal formula =1
Gender= female (0)
First ray neutral position= .00
Family history= yes (1)
Digital formula = 1

Applying Equation 4.8 to this data yields a predicted first metatarsophalangeal joint angle of 8.84°; the observed angle was measured at 10^0 using the Kilmartin finger goniometer. Thus, the prediction appears to agree well with the observed angle, since the difference between the observed and predicted angles is within the minimal detectable difference of the finger goniometer (2°).

By manipulation of the model it is possible to predict, within statistical limits, the magnitude of this females first metatarsophalangeal joint angle in the future, for example, when she is 50 years old.

It was shown in Section 4.5 that arch height index demonstrated a significant linear relationship with time. Therefore, this variable must first be adjusted to its predicted value at the required age, in this case 50 years old. Age adjustment is performed using Equation 4.9.

(Equation 4.9)

$\delta Y = (b1\ \delta X)$

Where:
δY= adjustment factor
b1= linear regression coefficient=0.004636
δX= difference between actual age and age at prediction =30

Solving equation 4.9 yields:

0.13908= (0.004636x30)

Addition of the adjustment factor to the original arch height index gives:

0.13908 + 0.40 = 0.53908

Solving Equation 4.8 with:

Arch height index=0.54
Age=50
Metatarsal formula =1
Gender= female (0)
First ray neutral position= .00
Family history= yes (1)
Digital formula = 1

This yields a predicted first metatarsophalangeal joint angle of 18.54° (8.79°, 28.29°). Thus, when this female is 50, the model predicts that there is a 95% chance that her first metatarsophalangeal joint angle will be between 8.79° and 28.29°. Since the confidence limits are large and straddle the delineation between normality and abnormality, it is uncertain whether this individual will develop hallux valgus or not. However, as before the probability of the angle being beyond the abnormal threshold can be calculated. Approximately 68% of the 95% confidence interval range lies beyond the abnormal threshold; therefore, there is a probability of 0.68 that she will develop hallux valgus.

CHAPTER V

DISCUSSION OF RESULTS

5.1 Introduction

This chapter provides interpretation and discussion of the results presented in the preceding chapter (IV). The chapter is again divided into two parts: Part I (Sections 5.2- 5.7) presents considerations of the results of the genetic analyses and estimations of heritability. Part II (Sections 5.8-5.15) addresses the predictors of 1st MPJ angle and proposes theoretical mechanisms of hallux valgus formation in association with these factors. The clinical implications of the study and suggestions for further research are presented in the final chapter (VI) together with the conclusions of the study.

PART I

5.2 The Heritability of Foot Measurement Variables

The narrow sense heritability estimates for the foot measurement variables primarily served to answer the question of whether genetic influences are important in the variation of the measured variables within the sample. Secondly, the estimates allowed the quantification of the magnitude of the genetic and environmental components of variation, so that the relative contribution of genetic and environmental influences to the observed phenotypes could be assessed.

From Table 4.13 it can be seen that estimates of heritability for all of the foot measurement variables are >0. It may be inferred, then, that genetic influences are present in the variation of all of the foot measurement variables to greater or lesser degrees.

In the remaining sections of this part of the chapter (Sections 5.3- 5.8) the heritability estimates for the foot measurement variables are examined in greater detail. The relative contributions of the genetic and environmental influences in each foot measurement variable is examined and theoretical mechanisms regarding the effects of these influences on the foot measurement variables are proposed.

5.3 The Heritability of First Metatarsophalangeal Joint Angle

A gender influence appears to exist in the narrow sense heritability estimates for 1st MPJ angles (Table 4.8). When both parent and offspring data were from the same gender, higher estimates were observed, suggesting that sons are more like their fathers and daughters are more like their mothers in terms of 1st MPJ angle. This is reflected in the observation of a significant statistical difference between male and female 1st MPJ angles (P=0.000, Table 4.4). Female offspring on female parent regression yielded a slightly higher estimate of heritability (0.88 ± 0.08) than the male offspring on male parent regression (0.76 ± 0.08). However, when the standard errors of the estimates are taken into consideration the estimates cannot be considered as significantly different.

When the averages of male and female offspring on male parent regressions and the averages of male and female offspring on female parent regressions were calculated, the heritability estimates of 1st MPJ angle in males and females within the sample were approximately 0.61 ± 0.08 and 0.78 ± 0.08 respectively (Table 4.13). Again, taking into account the standard errors of the estimates, the estimates for both genders cannot be considered as significantly different. These estimates of heritability are high, suggesting that genetic factors significantly contribute to the variability of 1st MPJ angle. This supports the contentions of earlier workers who believed that genetic predisposition was significant in the aetiology of hallux valgus (Hardy and Clapham 1951, Mitchell et al. 1958, Glynn et al. 1980, Kilmartin and Wallace 1990). However, the age adjustment of offspring data may have inflated the estimates of heritability. Although the age adjustment process was necessary since 1st MPJ angle is strongly influenced by age (when applied in isolation, age accounted for approximately 36% and 42% of the variance in 1st MPJ angle in males and females respectively (Tables 4.6- 4.7, Figures 4.25-4.28)), the method used to age adjust offspring data assumed that environmental factors are constant. This was because the age adjustment process was based upon linear regressions of 1st MPJ angle on age (Equation 4.3). Although, linear models were appropriate to describe the relationships between 1st MPJ angle and age in males and females (Section 4.5, Tables 4.6-4.7), they assume that the rate of change in 1st MPJ angle with age is constant, and identical for all males and all females.

Since, environmental influences play a role in the determination of 1st MPJ angle (Table 4.13), the rate of change in 1st MPJ angle with age is likely to be, in part, dependent upon the environment the foot is exposed. The rate of change is likely to vary, therefore, due to changes in the environment. But, because the age adjustment process is linear and based upon the rate of change of 1st MPJ angle with age obtained from a sample at a specific point of time, it assumes that all males and all females are exposed to the same, shared environments that are constant and fixed at the point of time that the data was obtained from the sample. Therefore, when age adjustment of offspring data was performed, the 1st MPJ angles were adjusted to the magnitude they should be, if the offspring were exposed to the same environment as their parents. Thus, the genetic components are likely to have been inflated by shared environmental components. Environment is not constant: therefore, the offspring are unlikely to be exposed to the same environment as their parents. Within a shod population the principle environment of the foot is the shoe. From a historical perspective the style of female footwear appears to alter more appreciably due to changes in fashion over time than does male footwear. Thus, it may be hypothesised that greater inaccuracy is likely to exist in the female estimate. A degree of caution is therefore required in the interpretation of these results.

A highly significant statistical difference was identified between male and female 1st MPJ data (P=.000, Table 4.4). The angles in males were generally lower than in females. Indeed, the mean male angle was within normal limits (<15°) while the female mean fell within the abnormal range (≥15°). The female prevalence of hallux valgus within the sample, indicated by a 1st MPJ angle ≥15°, was almost double that of the males (males =32%, females =62%). The observed differences in prevalence supports the general consensus of opinion that the deformity is more prevalent among females (Table 2.4).

Two possible explanations for the observed higher prevalence of hallux valgus among females may be proposed: i) females may be genetically predisposed to higher 1st MPJ angles than males or, ii) the environment that the female genotype is exposed to is more detrimental to the 1st MPJ angle than the male environment. Clearly, a third explanation, in which the increased prevalence among females is due to a combination of both of the above hypotheses is also possible.

There is little difference between the magnitude of the genetic components for males and females (Table 4.13) but, in general, strong differences in environment, in terms of footwear, do exist between genders. This appears to support the theory of footwear as a cause of hallux valgus, proposed by Shine (1965), who believed that the higher prevalence of hallux valgus observed among females was the result of an unfavourable interaction between the female genotype and the type of shoes habitually worn by this gender. The relatively low prevalence of hallux valgus, and the similarity between genders (in terms of 1st MPJ angle) observed in unshod populations, adds further support to this theory (Fook and Hodgson 1958, Shine 1965, Maclennan 1966). The effects of footwear on the kinematics of gait described by Schwartz and Heath (1959), Gastwirth et al. (1991), McBride et al. (1991) and Phillips et al. (1991), may account for the greater, more detrimental influence of female footwear on 1st MPJ angle. Since female footwear is generally tighter, more pointed and pitched for a higher heel than male footwear (Sussman and D'Amico 1984), it is likely to lead to a greater degree of trauma and overuse of the foot, specifically at the 1st MPJ, than male footwear. Such trauma and overuse may result in hypermobility and deformity. This could in-turn result in further trauma, increased hypermobility and greater deformity. Thus, a vicious circle may be formed.

Although the heritability estimates for 1st MPJ angle may be too high, due to the age adjustment of offspring data, 1st MPJ angle does appear to be strongly influenced by genetic factors (Table 4.13). Since the proportions and anatomy of the foot are the same in both genders (Cralley et al. 1976), anatomical differences seem unlikely to account for the increased female prevalence. A possible explanation appears to lie in hormonal differences between genders: specifically, the reported link between female hormones and ligamentous laxity (Schuster and Port 1977, Bird 1983). If hormonal differences between genders and their link with the female propensity for inherited ligamentous laxity are significant in the development of hallux valgus (Cralley et al. 1976, Grode and McCarthy 1980, Marr and D'Abrera 1985, Pressman 1987, Kalen and Brechner 1988, Carl et al. 1988, Bouysset et al. 1991) (Section 2.4), then females that are genetically predisposed to lax ligamentous structures of the foot, particularly at the 1st MPJ and 1st metatarsocuneiform joint, are more likely to have feet that are unstable and more easily traumatised by environmental stimuli such as footwear. Again, the vicious

circle of trauma-hypermobility-deformity, may ensue. Thus, even if genetic factors are responsible for the initiation of the loss of stability and equilibrium, once the destructive cycle has started, environmental factors are likely to become significant in the propagation and exacerbation of the cycle.

1st MPJ angle displays the characteristics of a gender influenced multifactorial trait. Both genetic and environmental influences have a role in the determination of 1st MPJ angle. The level of gene expression (the magnitude of the 1st MPJ angle) and, thus, the severity of hallux valgus, appears to be gender dependent. The magnitude of the 1st MPJ angle seems to be primarily influenced by the interaction of two factors:

1) The degree of hypermobility within the foot. This may be inherited or acquired due to overuse and abnormal functioning of joints.

2) The magnitude and direction of the forces applied to the foot. This appears to be strongly influenced by the design and fit of the footwear worn (Schwartz and Heath 1959, Gastwirth et al. 1991, McBride et al. 1991, Phillips et al. 1991).

5.4 The Heritability of Arch Height Index

The narrow sense heritability estimates for AHI displayed similarity to the estimates for 1st MPJ angle in that the estimate appears to be gender influenced (Table 4.9). When both parent and offspring data were from the same gender, higher estimates were yielded. However, there was little difference in the estimates of male offspring on male parent (0.43 ± 0.09) and female offspring on female parent (0.44 ± 0.06). Averaged heritability estimates for males and females of 0.35 ± 0.09 and 0.30 ± 0.08 respectively were calculated (Table 4.13). Again, taking into account the standard errors of the estimates, the estimates cannot be considered to be significantly different between genders and, therefore, population heritabilities are likely to be the same. The low heritability estimates indicate that environmental factors seem to be of greater significance than genetic / shared environmental factors. It may be inferred that, although shared genetic and / or shared environmental factors have a role in the determination of AHI, environmental factors (e.g. shoes and hosiery) have a greater role. Indeed, if the

age adjustment process did inflate the shared environmental components (Section 5.1) the role of shared genetic factors is likely to be even smaller than the estimate suggests, with the variance in AHI being almost completely under the control of environmental factors and strongly influenced by functional adaptation.

Although no statistical difference was observed in heritability estimates of AHI for the two genders, a statistically significant difference was observed between male and female arch height indices (P= 0.000, Table 4.4), with females generally displaying higher AHI (lower medial longitudinal arches). Again, the differences in environments that males and females are exposed to may account for the differences observed in AHI. Moreover, if this assumption is correct, the female environment appears to lead to lower medial longitudinal arch heights than the male environment. Didia and Nyenwe (1988) and Rao and Joseph (1992) supported the theory that habitual shoewearing leads to a decrease in the height of the medial longitudinal arch. Rao and Joseph (1992) believed that a restriction in intrinsic muscle activity formed the mechanism of the decrease in AHI. This may have an effect on the degree of hypermobility within the foot (Bird 1983). However, a further mechanism for this potentially lies in the effect of shoe heel height on ankle joint dorsiflexion. Heel height is believed to have a significant role in the development of accommodative shortening of the calf muscles. Passive stretch of these muscles during joint flexion-extension is an important factor in the maintenance of the normal physiologic length. Reduction of the stretch stimulus may lead to accommodative shortening of the muscles. The wearing of shoes with a heel pitch reduces tension in the calf muscles and may produce a functional shortening of the muscles. This may reduce the range of dorsiflexion available at the ankle joint. Root et al. (1977) proposed that 10° of dorsiflexion at the ankle before heel lift during gait was the minimum requirement. If this motion is not available at the ankle joint it may be made available through compensatory pronation of the subtalar and midtarsal joints. Such abnormal pronation is likely to lead to hypermobility, not only because abnormal rearfoot pronation unlocks the midtarsal complex and renders the forefoot hypermobile, but also because the stretching of ligaments that would ensue as joints are used beyond their normal functional range is likely to result in a degree of ligamentous laxity (Bird 1983), overuse and trauma. The effect may be magnified with increasing heel pitch. Sussman and

D'Amico (1984) measured the heel height of 200 shoes and noted that on average the heel height of female shoes was 2.5 times higher than that in male shoes. Clearly, the potential for a reduction in ankle dorsiflexion and consequential compensatory pronation is higher among females. This increased potential may account for the preponderance of higher AHI observed among females within the sample and for the greater amount of variance in AHI accounted for by age in the females (females 36%, males 17%, Tables 4.6-4.7). Moreover, if abnormal pronation is a causative factor in hallux valgus, it may account for the higher prevalence of affected females within the sample.

As before, the role of genetic differences between genders in the development of a higher AHI cannot be ruled out entirely by this study, since a genetic influence is seen in AHI. If hormonal differences between genders and their link with the female propensity for inherited ligamentous laxity are significant in the development of pes planus (Schuster and Port 1977, Bird 1983), then females that are genetically predisposed to lax ligamentous structures of the foot are more likely to have feet that are unstable and more easily traumatised by environmental stimuli such as footwear. Again, the vicious circle of trauma-hypermobility-deformity, may ensue. However, although a genetic predisposition may initiate collapse of the medial longitudinal arch, once initiated environmental stimulus will almost certainly play a role in the propagation of a destructive cycle.

5.5 The Heritability of First Ray Neutral Position

As before, gender influences were observed in the heritability estimates for 1st RNP (Table 4.10). Averaged heritability estimates of 0.43 $\pm$ 0.13 and 0.51 $\pm$ 0.11 (Table 4.13), were calculated for males and females, respectively. Again, taking into account the standard errors of the estimates, statistically, the population estimates of heritability are likely to be the same in males and females. In both genders a near even balance of genetic (and/or shared environment) and environmental factors appears to account for the variance in 1st RNP.

1st RNP is dependent upon the range of plantarflexory and dorsiflexory motion available at the joints of the first ray. Two factors are likely to govern these amounts of plantarflexion and dorsiflexion: the morphology of the bones and joints of the first ray and the tension in soft tissue structures surrounding

these joints. It would appear likely that genetic factors initially determine the morphology of the bones and joints of the first ray and the tension of soft tissue structures that encompass the joints. However, strong environmental modification of these structures appears to occur in response to functional requirements. Modifications of internal bone structure and external form and function are known to occur in response to the functional stresses placed upon them in accordance with Wolff's law (Brahm 1988). Such modification in the bony architecture may limit dorsiflexory or plantarflexory motion of the first ray and, therefore, affect the 1st RNP. Soft tissue structures are also likely to be effected by alteration in functional requirements of the foot in accordance with Davis's law. This suggests that an overall reduction or increase in soft tissue tension may occur on either the dorsal or plantar aspect of the joints of the first ray. A genetic predisposition towards ligamentous laxity may be significant, but the initial stimulus for such functional adaptation may arise from habitual shoewearing, since shoes are believed to alter the forces acting upon the foot and the normal function of its joints (Schwartz and Heath 1959, Gastwirth et al. 1991, McBride et al. 1991, Phillips et al. 1991).

A statistically significant difference was identified between male and female 1st RNP data (P=0.008, Table 4.4). The means of both sets of data fell within the plantarflexed range; the female mean (-0.24 mm) was lower than the males (-0.14 mm). Consideration of these results in association with the gender prevalence of hallux valgus within the sample (males 32%, females 62%) appears to support the contentions of Kilmartin, Wallace and Hill (1991) that a plantarflexed 1st RNP was significant in hallux valgus. The lack of statistical difference between heritability estimates for 1st RNP between genders, in association with a significant statistical difference between male and female 1st RNP data, reinforces the theory of footwear as a source of environmental stimulus of modification. Again, the unlocking of the forefoot due to the abnormal pronation induced by the habitual wearing of shoes which are narrow, pointed and pitched with a high heel, may be responsible for a reduction in tension in the ligamentous structures surrounding the joints of the 1st ray due to their abnormal functioning and overuse. This is then likely to initiate the destructive cycle of trauma-hypermobility-deformity, which has been previously discussed (Sections 5.3, 5.4).

5.6 The Heritability of Metatarsal Formula

The heritability estimates for metatarsal formula were high in both genders (Table 4.11). Although the female estimate was higher than the males (male = 0.65 ± 0.14, female = 0.86 ± 0.12, Table 4.13), taking the standard errors into account they cannot be considered to be statistically different. The high heritability estimates suggest that metatarsal formula is almost completely determined by genetic/shared environmental factors and that non-shared environment has little effect. Thus, it seems likely that metatarsal formula is determined at the time of fertilisation and remains relatively constant throughout life. This theory is further supported by the weak relationship observed between metatarsal formula and age (Tables 4.6- 4.7), and is consistent with the contentions of Craigmile (1953) and, later, McCarthy and Gessner (1993). However, both male and female estimates did contain an environmental component; therefore, some adaptation due to environmental stimulus may occur.

The theory of 2nd metatarsal enlargement proposed by Morton (1930) may provide an understanding of the mechanism by which environmental factors influence metatarsal formula. Morton (1930) believed that, in the presence of a dysfunctional 1st ray, a greater proportion of the ground reaction forces were located through the 2nd metatarsal head. As a consequence of this increased loading, Morton (1930) believed that the 2nd metatarsal enlarged. Clearly, enlargement of the 2nd metatarsal may alter the metatarsal formula, and thus the phenotype, provided that the 1st metatarsal is initially the longest (if the 2nd metatarsal is initially the longest, no change in metatarsal formula will be observed). However, the small environmental component within this sample suggests that this does not commonly occur as a response to environmental stimulus such as footwear and that little environmental modification does occur. Alternatively, it is possible that such lengthening of the second metatarsal does occur, but the lengthening is not of sufficient magnitude to alter metatarsal formula. Thus, although the method employed to evaluate metatarsal formula proved adequate to provide an estimate of heritability, its scale may have led to a lack of sensitivity.

The theory of 2nd metatarsal lengthening proposed by Morton (1930) does not account for a change in metatarsal formula that may result from a lengthening of the 1st metatarsal, such that the length of the 1st metatarsal exceeds the length of the lesser metatarsals in a foot where one or more of the lesser metatarsals were originally longer than the first. Although it is uncertain whether this actually occurs, a similar process to that described by Morton (1930) for lengthening of the second may be responsible. However, an alternative explanation appears to lie in the effect of the height of the medial longitudinal arch on first metatarsal length (Shereff et al. 1990, Lord et al.1992). It is possible that the lengthening/shortening of the foot that occurs because of lowering/raising the medial longitudinal arch may result in relative protrusion of the first metatarsal when the arch is lowered and relative protrusion of the lesser metatarsals when the arch is raised.

Clearly, this may explain why a statistically significant difference existed between male and female metatarsal formula data (P=0.000, Table 4.5), with more females than males displaying relative protrusion of the first metatarsal (males=49.6%, females 67.9%) given that, in general, the females displayed higher AHI (lower medial longitudinal arches) than the males. However, since AHI is age dependent (Tables 4.6-4.7, Figures 4.27-4.28), if this theory is correct one might expect metatarsal formula also to change with age. This was not observed, but as previously stated the method used to determine metatarsal formula may not have been sensitive enough to detect such changes. It is possible that the observed AHI are a consequence of relative metatarsal protrusion. A long first metatarsal is assumed to augment the lever arm of the hallux, which is in turn subjected to impaction from footwear. The direction of the force vector induced by this impaction may result in adduction of the first metatarsal (Duke et al. 1982). It is possible that such deviation of the metatarsal may result in pronation of the foot and consequential lowering of the medial longitudinal arch.

5.7 The Heritability of Digital Formula

The heritability estimates for digital formula were again gender influenced, with estimates of 0.84 ± 0.14 and 0.58 ± 0.11 being obtained for males and females respectively (Tables 4.12-4.13). This difference must be seen as real since the standard error ranges are discrete. The high male estimate suggests that digital formula is almost completely determined by genetic / shared environmental factors and that non-shared environment has little effect. Thus, it seems likely that digital formula in males is determined similarly to metatarsal formula, at the time of fertilisation, and remains relatively constant throughout life, little influence being had by the environment. However, environmental influences were more significant in the female estimate. Clearly, the mechanisms described in the preceding section to explain alteration in metatarsal formula are applicable to digital formula, since any change in metatarsal formula is likely to result in a change in digital formula.

Again, this may explain why a statistically significant difference existed between male and female digital formula data (P=0.001, Table 4.5), with more females than males displaying relative protrusion of the hallux (males=47%, females 57%) given that, in general, the females displayed higher AHI (lower medial longitudinal arches) than the males. However, since AHI is age dependent (Tables 4.6-4.7, figs.4.27-4.28), as before, if this theory is correct one might expect digital formula also to change with age. This was not observed, but again the method used to determine digital formula may not have been sensitive enough to detect such changes. Moreover, it is again possible that the observed AHI are a consequence of digital formula. The overlong hallux is likely to be subjected to impaction from footwear. The direction of the force vector induced by this impaction may result in abduction of the hallux and adduction of the first metatarsal (Duke et al. 1982). It is possible that such deviation of the metatarsal may result in a medial collapse of the foot and consequential lowering of the medial longitudinal arch.

However, it is possible to present a further, simpler, mechanism for alteration of digital formula in response to an increased 1st MPJ angle: as the 1st MPJ angle increases, the distal protrusion of the hallux decreases. In severe hallux valgus, the hallux over-rides / under-rides the second toe and consequently the second toe becomes the most distally protruding and the digital formula is changed.

The increase in 1st MPJ angle, and therefore the amount of modification in digital formula that occurs, is likely to be dependent upon the degree of hypermobility within the foot (inherited or acquired) and the magnitude and direction of the forces applied to the foot. This may explain the increased environmental component observed among females, since females are likely to display a greater degree of hypermobility (Bird 1983) and are generally more likely to be exposed to more detrimental forces due to the type of shoes habitually worn (Sussman and D'Amico 1984, McBride et al. 1991).

PART II

5.8 Predictors of Hallux Valgus

In the preceding chapter (Section 4.7) a mathematical model was developed that relates 1st MPJ angle (and thus hallux valgus) to several predictor variables, specifically: AHI, age, metatarsal formula, gender, 1st RNP, family history and digital formula. When this model was tested using a subset of data it was found that 92% of the observed 1st MPJ angle measurements fell within the 95% confidence intervals predicted by the model (Figure 4.65). Therefore, the model appears to be 92% accurate in the prediction of hallux valgus. However, as the mean 95% confidence intervals of prediction are relatively large ($\pm$ 9°), caution is required. Even though the model accurately predicted the 1st MPJ angle in 92% of cases, the model may have over-estimated or under-estimated the 1st MPJ angle in these individuals by up to 9°. In the remaining 8% of individuals, the error in estimation was >9°. When tested the mean error in estimation was + 0.4° (S.D. $\pm$ 5.51°) (Figure 4.66). In real terms this means that in 68% of individuals whose 1st MPJ angles were predicted using the model, the error in prediction was less than $\pm$6°. The error in prediction in the remaining 32% of individuals was larger than this. Thus, whenever a prediction is made using this or any other predictive model, the confidence limits of the prediction should be carefully examined before any clinical decision is made.

The remainder of this chapter (Sections 5.9-5.15) focuses on each of the predictors in turn. The relationships between the predictors and 1st MPJ angle are discussed and theoretical mechanisms for the development of hallux valgus in association with the predictors are presented. The conclusions of the study and the clinical implications of the study are discussed in the succeeding chapter (VI).

5.9 Arch height index

The strongest predictor of 1st MPJ angle (and thus hallux valgus) was AHI (Table 4.14). A positive correlation between 1st MPJ angles and AHI was observed within the sample. This suggests that, as the AHI increases (that is, the height of the medial longitudinal arch decreases, and the foot becomes more pronated), the 1st MPJ angle increases. This result supports the theory of a relationship between hallux valgus and foot pronation previously reported in the literature (Riedel 1886, Goldthwait 1893, Root et al. 1977, Greenberg 1979, Kalen and Brecher 1988). However, the existence of a relationship does not determine cause and effect. Although a strong association between 1st MPJ angles and AHI was observed, it should be noted that despite the high prevalence of hallux valgus within the sample (49%), most of the AHI fell within the normal range (0.30 - 1.0) reported by Staheli et al. (1987). Indeed, many of the highest 1st MPJ angles were associated with AHI of approximately 0.8. Thus, either the relationship between abnormal pronation and hallux valgus must be questioned, or the normal range for AHI reported by Staheli et al. (1987) must be questioned.

It is difficult to make judgement concerning the adequacy of Staheli's results. However, Staheli et al. (1987) did base their results on a large series of normal individuals (n=441) and reported that subjects were selected from non-orthopaedic outpatient clinics and that none reported a history of musculoskeletal abnormality. This was obviously their definition of normality and would appear adequate. However, normality is inherently difficult to define, since that which may be considered as normal for one individual may not be for another.

If Staheli's normal limits are adequate, the significance of abnormal pronation as an aetiological factor in hallux valgus must be questioned. However, a trend does exist between AHI and 1st MPJ angles

within the sample. Thus, if the observed indices are not within normal limits (i.e. the limits for normality proposed by Staheli et al. (1987) are rejected) the role of abnormal pronation in the deformity must be considered as significant and addressed. However, the problem of delineation between cause and effect remains.

It is possible to provide two hypotheses that may account for the relationship observed between 1st MPJ angle and AHI. The first suggests a mechanism whereby the increase in 1st MPJ angle occurs in response to an increase in AHI, and the second presents a mechanism in which the increase in AHI occurs in response to an increase in 1st MPJ angle:

Root et al. (1977) contended that abnormal rearfoot pronation renders the forefoot hypermobile during gait and prone to deforming forces. These forces are assumed to increase the lateral deviation of the hallux on its metatarsal. Clearly, if the joints of the forefoot are hypermobile, the deforming forces of footwear may have a significant effect on the bony relationships and lead to plastic deformation of the forefoot. The increased forces associated with narrower female footwear may account for the greater hallux deviation observed among females. Moreover, AHI of males and females were significantly different (P=0.000, Table 4.4), the female indices tending to be higher. If the theories of Root et al. (1977) are accepted, this in isolation may result in more females displaying hypermobility of the forefoot and thus account for the higher prevalence of the deformity observed among females. Furthermore, most individuals exhibit an abducted angle of gait to a greater or lesser degree. In the presence of foot pronation, the angle of abduction is believed to increase (Miller 1960). This may result in lateral deviation of the hallux when the forefoot is hypermobile, since the force vector induced at toe-off is directed increasingly laterally through the hallux as the angle of gait becomes more abducted (Snijders et al. 1986). Thus, this hypothesis of pronation as a cause of increased 1st MPJ angle appears plausible.

A further hypothesis of pronation as an effect of increased 1st MPJ angle may be presented in a simplified model: If the foot is considered as a tripod, the three points of contact being the heel, the 1st MPJ and the 5th MPJ, deviation of the first metatarsal towards the midline of the body associated with an increase in 1st MPJ angle (the metatarsus primus varus component of hallux valgus) may result in

medial collapse of the tripod and consequential lowering of the medial side of the foot. Thus, pronation of the foot may be secondary to an increase in 1st MPJ angle that is itself secondary to another factor(s).

5.10 Age

Age was the second independent variable entered into the model and was therefore the second best predictor of 1st MPJ angle when AHI is taken into consideration. 1st MPJ angles increased with age within the sample. This reflects the results of Maclennan (1966). Interestingly, from Figures 4.25 and 4.26 it is evident that the female rate of change of 1st MPJ with age was slightly greater than the male (females b=0.264, males b= 0.200). Furthermore, the intercept value in the female data was higher than in the male data (females 8.07, males= 6.21). The intercept value is the theoretical estimate for 1st MPJ angles for an age of zero years assuming a constant rate of change for early years. It may be inferred (assuming a linear relationship), therefore, that females are born with higher angles than males, and that the female angles increase more rapidly with time than do male angles.

The literature provides little evidence to support this hypothesis. Indeed, the author is unaware of any studies that have measured 1st MPJ angles in new born children. The observation that female angles increased more rapidly with time than male angles supports the results of Shine (1965) who noted a faster rate of change in 1st MPJ angle with the length of time for which shoes had been worn among females (females b=0.04266, males b= 0.01685), suggesting that differences in the type of footwear habitually worn by each gender were responsible for the differences in the rates of progression of 1st MPJ angles. Several authors have noted a higher prevalence of juvenile hallux valgus among females (Cole 1959, Marr and D'Abrera 1985, Brodie et al. 1988, Kilmartin and Wallace 1994). It is possible that higher initial angles among females, with a slightly faster rate of change of 1st MPJ angles with time, may account for more females displaying the deformity at an earlier age than males. Given the evidence provided, the angle will reach the abnormal threshold of 15° in females before it does in males. Caution is clearly required, however, since the observation of a higher initial angle in females is based on an extrapolation of data.

The sample was drawn from a shod population. Thus, the relationship between the 1st MPJ angles and the length of time for which shoes had been worn may serve to obscure the relationship between the angles and age. The reported low prevalence of hallux valgus among unshod populations (Fook and Hodgson 1958, Maclennan 1966), and the rapid increase in angle following the transition from barefoot to shod walking irrespective of age reported, by Shine (1965) supports this theory, suggesting that progression of the angle is not dependent upon age alone. Thus, it may be argued that the relationship between 1st MPJ angles and age is a reflection of the relationship between 1st MPJ angles and the length of time for which shoes have been worn. It may be hypothesised that the 1st MPJ angle increases with the length of time for which shoes have been worn, if this supposition is accepted. This supports the contentions of Shine (1965). Moreover, "female footwear" may increase the angle more rapidly and to a greater extent than "male footwear", a theory previously supported by Barnicott and Hardy (1955). Clearly, differences exist in male and female shoe design. The consequence of these differences in design may be an increase in forces or the impulse of force acting on the forefoot among females (Hoffman 1905, James 1939, Schwartz and Heath 1959, Sussman and D'Amico 1984, Gastwirth et al. 1991, McBride et al. 1991, Phillips et al. 1991). Shoes that are narrower and more pointed at the toes may magnify these effects to a greater extent than shoes that are wider and less pointed.

The human foot is essentially plastic. Perhaps the most dramatic example of plastic deformation of the foot comes from the ancient Chinese practice of foot binding that results in a foot reduced to approximately one-third of its original length (Hawes et al. 1994). Foot binding results in excessive forces being applied to the foot. Clearly, such forces are greater than those resulting from shoe wearing. However, given the evidence provided, the type of footwear habitually worn may be responsible for modifying the shape of the foot, specifically the 1st MPJ angle.

5.11 Metatarsal Formula

The third independent variable entered into the model, and thus the third best predictor of 1st MPJ angle in association with AHI and age, was metatarsal formula. A positive correlation was observed between 1st MPJ angle and metatarsal formula. This suggests that high 1st MPJ angles are more likely to occur in the presence of relative protrusion of the 1st metatarsal and that lower 1st MPJ angles are likely to be associated with relative protrusion of one or more of the lesser metatarsals. Within the sample, 82% of males and 84% of females displaying hallux valgus also displayed relative protrusion of the first metatarsal. This appears to support the theory of relative protrusion of the first metatarsal as an aetiological factor in hallux valgus previously reported in the literature (Nilsonne 1930, Hardy and Clapham 1952, Plaster 1954, Heden and Sorto 1981, Duke et al. 1982). On the basis of these results the contentions of DuVries (1973), Inman (1974) and, later, Saragas and Becker (1995) who believed that relative metatarsal length had no direct importance in hallux valgus and that the deformity was commonly observed in association with both long and short first metatarsals, do not appear entirely correct. Notably, of those that did not display hallux valgus, 42% of males and 34% of females did exhibit relative protrusion of the first metatarsal. But, given the study findings, many of these individuals, particularly the females, may well progress to develop the deformity.

It is possible to hypothesise on the mechanism by which a relatively longer first metatarsal acts as an aetiological factor in hallux valgus. The lever arm of the hallux is augmented and the stabilizing effect of the second toe is reduced in the presence of protrusion of the first metatarsal. Furthermore, the restraining ability of the metatarsal cuneiform joint to oppose metatarsal adduction is decreased. Therefore, the hallux may adduct the metatarsal with less resistance and the medial longitudinal arch will be lowered. Lowering of the medial longitudinal arch increases midtarsal and subtalar joint pronation, leading to increased forefoot hypermobility. Less force is then required to induce an increase in 1st MPJ angle in the presence of first metatarsal protrusion due to the increased lever arm it provides. Male footwear appears likely to apply less force to the foot than female footwear. However, some application of force will still occur. When the first metatarsal is longer than the second metatarsal, the magnitude of this force may be sufficient to have detrimental effects. The application of similar force

to a foot that displays protrusion of the lesser metatarsals may have little effect since the lever arm of the first metatarsal is reduced. There is then no mechanical advantage over the second metatarsal and the second metatarsal has sufficient buttressing effect to prevent hallux deviation.

The above theory suggests that relative protrusion of the first metatarsal is responsible for the increase in 1st MPJ angle and possibly the increase AHI. However, cause and effect cannot be determined from correlation. Thus, it is possible to hypothesise on a mechanism in which the increased 1st MPJ angle brings about relative protrusion of the 1st metatarsal. In section 5.6 a theory regarding the relationship between the height of the medial longitudinal arch and first metatarsal length was presented. It was suggested that the lengthening / shortening of the foot that occurs because of lowering / raising the medial longitudinal arch may result in relative protrusion of the first metatarsal when the arch is lowered and relative protrusion of the lesser metatarsals when the arch is raised. In Section 5.9 a relationship between high 1st MPJ angle and low arch height was noted. Clearly, if the theory presented in section 5.6 is correct, then relative protrusion of the first metatarsal may occur as a result of the lowering of the medial longitudinal arch which may itself arise due to an increase in 1st MPJ angle (Section 5.9). However, as previously stated the apparent lack of change in metatarsal formula with age, and the high heritability estimates obtained for metatarsal formula, somewhat detract from this theory.

5.12 Gender

The fourth independent variable entered into the model, and thus, the fourth best predictor of 1st MPJ angle in association with AHI, age and metatarsal formula, was gender. Due to the coding applied to the gender variable (females =0, males =1) a negative association was observed between 1st MPJ angle and gender. This suggests that high 1st MPJ angles are more likely to occur among females and that lower 1st MPJ angles are likely to be associated with males. This association has previously been noted, and discussions on the role of gender in the aetiology of hallux valgus and its predisposing factors have

been developed in all of the preceding sections of this chapter. A further in depth discussion of the role of gender does not appear warranted here. Thus, a brief synopsis is presented.

The key factor which emerges from the discussions concerning gender is that it does not appear to be gender per se which is significant in the development of hallux valgus and/ or its predisposing factors. Rather, it is distinct differences that exist in the environments that the male and female foot are exposed to. In a shod population the magnitude and direction of the forces exerted on the foot are largely dependent upon the type of footwear habitually worn. Female footwear appears to exert forces of a greater magnitude and in directions that are more detrimental to the foot than male footwear (Sussman and D'Amico 1984, McBride et al. 1991). Although a female propensity for inherited ligamentous laxity may also be of significance in the development of hallux valgus and/or one or more of its predisposing factors, and cannot be ruled out as a significant actiological factor by this study, in essence it is not as important as the forces acting upon the foot. It seems fair to assume that in the absence of any force acting upon a hypermobile foot, it would remain free from deformity and that as the forces acting upon the foot increase in magnitude, so too should the degree of deformity. Therefore, if two identical feet (hypermobile or not, male or female) were exposed to differing forces, the foot exposed to the greatest forces, directed in more detrimental directions, is likely to display the greatest degree of deformity. Thus, it is the magnitude and direction of the forces acting upon the foot and, therefore, the environment the foot is exposed to, that is the key determinant of deformity not gender.

5.13 First Ray Neutral Position

The fifth independent variable entered into the model was 1st RNP. A negative correlation was observed between 1st MPJ angle and 1st RNP. This suggests that, as 1st MPJ angle increases, 1st RNP decreases. Within the sample, 61% of subject displaying hallux valgus also displayed a plantarflexed 1st RNP. Of the individuals who did not exhibit hallux valgus, only 27% displayed a plantarflexed 1st RNP.

This appears to support the theory of a relationship between 1st MPJ angle and 1st RNP previously described by Kilmartin, Wallace and Hill (1991). However, these previous workers maintained that a position in excess of 2mm plantarflexed was significant. Within the present sample only 1% of the

individuals displaying hallux valgus had a 1st RNP in excess of 2mm plantarflexed. Since Kilmartin, Wallace and Hill (1991) included no zero position in their calculation of 1st RNP, they should actually be advancing a position in excess of 1mm plantarflexed as significant. Within the present sample 29% of individuals displaying hallux valgus also displayed 1st RNP that fell within this range. It should be noted that the conclusions drawn by Kilmartin, Wallace and Hill (1991) were based on a population of adolescents. However, 1st RNP are unlikely to become increasingly dorsiflexed with age, since the relationship observed between these variable was only weak in both genders (Tables 4.6- 4.7). The negative correlation observed between 1st MPJ angle and 1st RNP also questions the contentions of Klaue et al. (1994) who reported that increased dorsiflexory mobility was observed in association with hallux valgus. An increase dorsiflexory mobility should result an dorsal shift of the 1st RNP and a positive correlation with 1st MPJ angle. This was not observed.

It is possible to present a theoretical mechanism by which the plantarflexed 1st RNP may lead to an increase in 1st MPJ angle. The 1st RNP was measured non-weightbearing. Kilmartin, Wallace and Hill (1991) suggested that, on weightbearing, the non-weightbearing 1st RNP is unlikely to be maintained. If the plantarflexed 1st ray is pushed dorsally on weightbearing as Kilmartin, Wallace and Hill (1991) suggest, it is likely to be pushed beyond the level of the lesser metatarsals as suggested by Kilmartin, Wallace and Hill (1991). The anatomy of the 1st MPJ is unlike the lesser MPJ's; it has the added bulk of the sesamoid apparatus attached on its plantar surface. It seems logical that on weightbearing it is the plantar most aspect of the sesamoid apparatus that will be on the same horizontal plane as the most plantar aspects of the lesser MPJ's, and that the first metatarsal head will be dorsiflexed relative to the lesser metatarsals due to the added bulk beneath it. Within this sample high 1st MPJ angles were observed in association with plantarflexed 1st RNP, long 1st metatarsals and high AHI (low medial longitudinal arches). This suggests that the plantarflexed, long 1st metatarsal is pushed into dorsiflexion and the arch is lowered as described by Hicks (1954). Hamill et al. (1989) also noted this association between plantarflexed 1st RNP and decreased arch height. If the medial longitudinal arch is lowered, the degree of midtarsal and subtalar joint pronation is likely to be increased (Otman et al. 1988), unlocking the forefoot. In this pronated state, the forefoot is hypermobile and the angle of gait becomes

more abducted (Miller 1960). Since the force vector induced at toe-off is directed increasingly laterally through the hallux as the angle of gait becomes more abducted (Snijders et al. 1986), in the presence of forefoot hypermobility the hallux may be pushed into abduction, increasing the 1st MPJ angle. It seems likely that the degree of abduction that the hallux is forced into is dependent on the magnitude of the forces acting on the hallux and the degree of hypermobility present within the foot. Furthermore, both the magnitude of the forces and the degree of hypermobility may, in part, dependent upon the type of footwear habitually worn (Sussman and D'Amico 1984, McBride et al. 1991). Given the differences in male and female shoe design and the female propensity for ligamentous laxity, female footwear is likely to exacerbate the abduction of the hallux to a greater degree than male footwear. This may account for the increased female prevalence of hallux valgus.

5.14 Family History

The sixth independent variable entered into the model was family history. A positive correlation between 1st MPJ angle and family history was observed. Thus, the highest 1st MPJ angles were associated with a positive family history for hallux valgus while the lower 1st MPJ angles were associated with a negative family history for the deformity. This observation supports the contentions of many earlier workers who believed that hallux valgus ran in families, and had used the presence of a family history of the deformity to substantiate their conjectures that the deformity displayed the characteristics of an inherited trait (Hardy and Clapham 1951, Bonney and Macnab 1952, Johnston 1956, Mitchell et al. 1958, Glynn et al. 1980, Kilmartin and Wallace 1990, Coughlin 1995). Within the sample 88% of individuals displaying hallux valgus also had a positive family history for the deformity (positive family history denotes a family in which at least two members are affected). Of the individuals that did not display hallux valgus 41% had a positive family history of the deformity. However, given the authors findings, many of these individuals may develop the deformity with time.

The large percentage of individuals displaying hallux valgus in association with a positive family history for the deformity, when considered in association with the high heritability estimates for 1st MPJ angle (Section 5.2), appears to provide strong support to a hypothesis of genetically determined aetiology for hallux valgus. If this theory is correct, it appears that the deformity is most commonly

transmitted from mother to daughter. However, the mechanism for this transmission is unclear. The contention that hallux valgus is due to the expression of a single gene (Johnston 1956) appears incorrect. Hallux valgus appears to display the characteristics of a quantitative, polygenic trait, with varying degrees of hallux deviation existing within the population. Moreover, an environmental component appears significant in 1st MPJ angle (Section 5.3). Thus, hallux valgus must be considered as a multifactorial trait and not that of a trait caused by a single gene. Given the propensity of females displaying hallux valgus it appears that as well as being multifactorial, it is also gender influenced. As previously discussed (Sections 5.12) this gender influence may be the result of a female propensity towards inherited ligamentous laxity, but also, perhaps of greater significance, it may be due to the type of footwear habitually worn by this gender. Perhaps a good analogy here is baldness: baldness is more common in men than in women, even though equal numbers of both are heterozygote for the condition. The difference in prevalence between genders is due to the fact that it is the male environment, specifically the male hormones, that provide the essential ingredient for the gene to show itself (Cummings 1993). Similarly, but conversely, in the case of hallux valgus, it appears that it is the female environment, in terms of footwear that provides the essential ingredient and controls the manifestation of the condition.

A positive family history was not present in all cases of the deformity. This appears to detract from the genetic hypothesis and add weight to the argument that the environment influences are of greater significance than genetic predisposition in determining the magnitude of the 1st MPJ angle. As previously stated, the heritability estimate was inflated by the method used to age adjust the data and is unlikely to be as high as it appears. Thus, environmental influences are likely to be stronger than they appear. It should be noted however, that the lack of a positive family history may have been due to too few members of a family being measured. It is possible that a positive family history did exist but the other members of the family displaying the trait were not measured.

5.15 Digital Formula

Digital formula was the final variable entered into the model. The significance level associated with the digital formula coefficient t-value was 0.39; thus its addition to the model did not significantly improve the models ability to predict 1st MPJ angle at the P=0.05 level. This said, a positive association was displayed between 1st MPJ angle and digital formula. It may be inferred that relative protrusion of the hallux was commonly associated with a high 1st MPJ angle. This observation is consistent with those of Mayo (1908), McGlamry et al. (1970) and Heden and Sorto (1980) who reported that the characteristic of hallux valgus formation was a hallux that was longer than the second toe.

A theoretical mechanism by which an increase in 1st MPJ angle occurs in association with a long hallux may be presented. It may be assumed that an overlong hallux is subjected to impaction from footwear to a greater extent than a hallux which is shorter than its lesser digits. If this assumption is correct, based on the results of this study, it would appear likely that the direction and magnitude of the force vector induced by impaction from footwear, in association with an overlong hallux, is sufficient to cause changes in the range of motion in the joints of the 1st ray. These changes appear to result in a 1st RNP that is plantarflexed. The mechanism presented in section 5.13 for an increase in 1st MPJ angle in association with a plantarflexed 1st RNP may then ensue, leading to the development of hallux valgus. This hypothesis is partly supported by Hawes et al. (1994) who suggest that, in long distance runners, chronic stresses associated with repeated impaction were associated with plantarflexed 1st RNP. Obviously, stresses resulting from long distance running are likely to be excessive. However, the repeated impaction of the overlong hallux by footwear, over time, may be sufficient to cause changes in the range of motion available at the joints of the first ray, specifically a reduction in dorsiflexion and / or an increase in plantarflexion.

It seems likely that the magnitude and direction of the force vector induced by the impaction of the hallux on footwear is dependent on the type of footwear worn and that the degree of abduction observed at the 1st MPJ is dependent upon forces applied, in combination with the degree of hypermobility present in the foot. Hypermobility may be increased in females due to this gender's propensity for inherited ligamentous laxity (Bird 1983). The magnitude of the impaction force and the

degree of hypermobility will almost certainly be increased by the type of footwear habitually worn by this gender (Sussman and D'Amico 1984, McBride et al. 1991). Thus, a greater potential for increased 1st MPJ angle exists among females. This may account for the greater prevalence of hallux valgus observed among females.

CHAPTER VI

CONCLUSIONS, CLINICAL IMPLICATIONS & RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Introduction

This final chapter first draws together the findings of the study, deriving conclusions from the results obtained (Section 6.2). Following this summation, the clinical implications of the study are defined and recommendations for improvements to clinical practice are made (Section 6.3). Finally, consideration is given to future research regarding hallux valgus; implications and directions for this research are outlined (Section 6.4).

6.2 Conclusions

The literature relating to hallux valgus identifies genetic inheritance, gender, age, footwear, pes planus / pronation, metatarsal formula, digital formula and first ray position as potential aetiological factors in hallux valgus. This study identified and appraised methods to evaluate the significance of these factors in hallux valgus. These methods were applied to a large sample of genetically related individuals. The aetiology of hallux valgus was explored through the statistical analyses of the data obtained from this sample. This systematic analysis of data has provided a statistical model that relates the degree of hallux deviation at the first metatarsophalangeal joint (and thus, the degree of hallux valgus) to clinically measurable predictor variables. When tested this model was found to accurately predict the first metatarsophalangeal joint angle in 92% of cases. Application of the model allows the clinician to evaluate an individual's risk of developing hallux valgus and enables the prediction of prognosis. Thus, the study aim and objectives have been achieved. Several key conclusions may be drawn from the results of the study.

Hallux valgus is present in varying degrees within the population. The clear cut, dichotomous, distinction of "present or not", that is normally observed in traits arising from the expression of a single Mendelian gene, was not observed within the first metatarsophalangeal joint angle data. From the heritability analyses it is evident that both genetic and environmental influences have a role in determining the first metatarsophalangeal joint angle, but genetic influences appear to be larger than environmental influences. The mechanism of inheritance must therefore be considered as multifactorial. Although the proportions of genetic and environmental influences in first metatarsophalangeal joint angle were similar in males and females, females displayed a greater propensity for higher first metatarsophalangeal joint angles. This suggests that the expression of the trait is gender influenced. Thus, it may be concluded that hallux valgus is a gender influenced multifactorial condition.

The magnitude of the first metatarsophalangeal joint angle, and thus the severity of hallux valgus, appears to be dependent upon the values of several predictor variables, many of which are themselves determined by the interaction of genetic and environmental influences, in varying degrees. A synopsis of each of the predictors of first metatarsophalangeal joint angle, identified in this study, follows:

6.2.1 Arch height index

The method of charting arch height indices from footprints described by Rao and Joseph (1992) was applied as a measure of pes planus / foot pronation. A positive correlation between first metatarsophalangeal joint angle and arch height index data was observed within the sample. This suggests that as the arch height index increases (that is, the height of the medial longitudinal arch decreases, and the foot becomes more pronated), the first metatarsophalangeal joint angle increases, or vice versa.

Arch height index, and therefore the degree of pronation present within the foot, also displayed the characteristics of a gender influenced, multifactorial trait, but with environmental influences having a stronger role than genetic. Females displayed a greater frequency of high arch indices than males. However, the proportions of the genetic and environmental influences could not be considered to be

significantly different between genders. Differences in the environments that males and females are exposed to may account for the differences observed in arch height index between genders. Specifically, the female foot is likely to be exposed to an environment which predisposes to an increase in the forces acting on the foot and to a greater degree of hypermobility within the foot. It is believed that these factors will result in lowering of the medial longitudinal arch and, thus, increased foot pronation. Increased foot pronation is likely to increase the hypermobility within the foot and modify the magnitudes and directions of the forces acting on it. This may perpetuate a destructive cycle of trauma-hypermobility-deformity. This cycle may result in an increase the first metatarsophalangeal joint angle and therefore, hallux valgus.

6.2.2 Age

First metatarsophalangeal joint angles increased with age. The female rate of change in first metatarsophalangeal joint with age was slightly greater than the male. This may account for more females displaying the deformity at an earlier age than males. The sample was drawn from a shod population. The relationship between the first metatarsophalangeal joint angles and the length of time for which shoes had been worn may therefore serve to obscure the relationship between the angles and age. The relationship between first metatarsophalangeal joint angle and age may then be a reflection of the relationship between first metatarsophalangeal joint angles and the length of time for which shoes have been worn. If this hypothesis is correct, it may be concluded that the first metatarsophalangeal joint angle increases with the length of time for which shoes have been worn. Differences in male and female shoe design may account for the differences observed in the rate of change in first metatarsophalangeal joint angle with age between genders. Female footwear may predispose to an increase in the forces acting on the foot and to a greater degree of hypermobility within the foot. Again, the destructive cycle of trauma-hypermobility-deformity may ensue resulting in hallux valgus.

6.2.3 Metatarsal formula

Palpation of the metatarsal heads was used to identify if the first metatarsal was longer or shorter than the lesser metatarsals; this measure was termed the metatarsal formula. A positive correlation was observed between first metatarsophalangeal joint angle and metatarsal formula, suggesting that high

first metatarsophalangeal joint angles are more likely to occur in the presence of relative protrusion of the first metatarsal and that lower first metatarsophalangeal joint angles are likely to be associated with relative protrusion of one or more of the lesser metatarsals. Within the sample, 82% of males and 84% of females displaying hallux valgus also displayed relative protrusion of the first metatarsal.

Metatarsal formula also appears to be a gender influenced multifactorial condition. Although the measurement scale meant that it displayed binomial variation within the sample, in reality metatarsal length is not a dichotomous, binomial parameter, it is a continuous variable. Thus, if metatarsal lengths had been quantitatively measured and a ratio of first metatarsal to the longest lesser metatarsal had been calculated, continuous variation is likely to have been observed. Both genetic and environmental influences were seen to be interacting in the determination of metatarsal formula, but the proportion of genetic influences was much greater than the proportion of environmental influences. Thus, it seems likely that metatarsal formula is determined at the time of fertilisation and generally remains the same throughout life. However, some adaptation due to environmental stimulus does appear to happen. It is believed this adaptation may occur in two ways: i) by elongation of the second metatarsal due to bone remodelling, and ii) by relative lengthening of the first metatarsal due to foot pronation. Both of these mechanisms are ultimately dependent upon the forces acting upon the foot. Despite similarity in the proportions of genetic and environmental influences in metatarsal formula between genders, a greater proportion of females displayed long first metatarsals. The greater potential for females to exhibit increased foot pronation may account for the greater proportion of females displaying a long first metatarsal.

The long first metatarsal is believed to augment the forces acting upon the foot and increase the hypermobility within the foot. Thus, this variable may also contribute to the trauma-hypermobility-deformity cycle which is believed to increase the first metatarsophalangeal joint angle and therefore, bring about hallux valgus.

6.2.4 Gender

The prevalence of hallux valgus in females and males was found to be in the ratio of 2:1. It may be concluded that higher first metatarsophalangeal joint angles are more likely to occur among females and lower first metatarsophalangeal joint angles are likely to be associated with males. Although hormonal differences between genders may be of significance, it appears likely that it is not gender per se which is significant in the development of hallux valgus and/or its predisposing factors. Rather, it is distinct differences that exist in the environments that the male and female foot are exposed to. In a shod population the magnitude and direction of the forces exerted on the foot are largely dependent upon the type of footwear habitually worn. Female footwear appears to exert forces of a greater magnitude and in directions that are more detrimental to the foot than male footwear, possibly resulting in a greater degree of trauma and hypermobility and therefore, a greater prevalence of hallux valgus.

6.2.5 First ray neutral position

First ray neutral position was measured using the methods described by Kilmartin, Wallace and Hill (1991). A negative association was observed between first metatarsophalangeal joint angle and first ray neutral position data. This suggests that, as first metatarsophalangeal joint angle increases, first ray neutral position becomes increasingly plantarflexed, and vice versa.

First ray neutral position also appears to display the characteristics of a multifactorial trait with gender influences. In both genders a near even balance of genetic (and/or shared environment) and environmental factors appear to interact to determine the first ray neutral position. Nevertheless, a greater proportion of females displayed plantarflexed first ray neutral positions than males. First ray neutral position is dependent upon the range of plantarflexory and dorsiflexory motion available at the joints of the first ray. Two factors are likely to govern these amounts of plantarflexion and dorsiflexion: i) the morphology of the bones and joints of the first ray, and ii) the tension in soft tissue structures surrounding these joints. Environmental modification of bone and or soft tissue in response to the forces acting upon the foot may result in modification of the first ray neutral position. Differences in the environment that each gender is exposed to may account for the observed differences in the first ray neutral positions of males and females.

The plantarflexed first ray is believed to increase forefoot hypermobility. In presence of forefoot hypermobility the hallux may be pushed into abduction, increasing the first metatarsophalangeal joint angle. It seems likely that the degree of abduction that the hallux is forced into is dependent on the magnitude of the forces acting on the hallux and the degree of hypermobility present within the foot. Furthermore, both the magnitude of the forces and the degree of hypermobility may, in part, dependent upon the type of footwear habitually worn. This may account for the increased female prevalence of hallux valgus.

6.2.6 Family history of hallux valgus

Family history was represented as a dichotomous variable. If two or more individuals from a given family group had a first metatarsophalangeal joint angle $\geq 15^{0}$ all members of the family were awarded a score of 1, indicating a positive family history for abnormally high first metatarsophalangeal joint angles, or hallux valgus. If only one member of a family group had a first metatarsophalangeal joint angle $\geq 15^{0}$ all members of the family were awarded a score of 0, indicating no family history for the deformity. Although this method was superior to the method commonly used to obtain family history information (verbally asking if other family members are affected) it was still prone to error due to the incomplete ascertainment of families.

A positive correlation between first metatarsophalangeal joint angle and family history was observed. Thus, the highest first metatarsophalangeal joint angles were associated with a positive family history for hallux valgus while the lower first metatarsophalangeal joint angles were associated with a negative family history for the deformity. Within the sample 88% of individuals displaying hallux valgus also had a positive family history for the deformity. Of the individuals that did not display hallux valgus 41% had a positive family history of the deformity. However, many of these individuals may progress to develop the deformity. Not all individuals displaying hallux valgus had a positive family history of the deformity. However, as previously stated, the incomplete ascertainment of families may have influenced this result.

6.2.7 Digital formula

Observation of the digital patterning of the foot on weightbearing was used to identify if the hallux was longer or shorter than the lesser digits; this measure was termed the digital formula. A positive association was displayed between first metatarsophalangeal joint angle and digital formula. It may be concluded that relative protrusion of the hallux was commonly associated with high first metatarsophalangeal joint angles.

Digital formula also appears to be a gender influenced multifactorial condition. Again, the measurement scale meant that data displayed binomial variation within the sample, but in reality digital length is not dichotomous, but continuously varying. Thus, if digital lengths had been quantitatively measured and a ratio of hallux length to the length of longest lesser digit had been calculated, continuous variation is likely to have been observed. Both genetic and environmental influences were seen to be interacting in the determination of digital formula, but differences were observed in the proportions of these influences between genders. Among males digital formula appears to be almost completely determined by genetic / shared environmental factors and non-shared environment has little effect. Thus, it seems likely that digital formula in males is determined similarly to metatarsal formula, at the time of fertilisation and remains relatively constant throughout life, with little environmental influence. However, environmental influences were more significant in the female estimate. Environmental adaptation may occur by the same mechanisms described for metatarsal formula: i) by elongation of bone due to remodelling and, ii) by relative lengthening of the hallux due to foot pronation. Both of these mechanisms are ultimately dependent upon the forces acting upon the foot. A greater proportion of females than males displayed relative protrusion of the hallux (males=47%, females 57%). The greater potential for females to exhibit increased foot pronation, in combination with the increased potential for the female foot to be exposed to deforming forces may account for the greater proportion of females displaying long hallux.

The overlong hallux is likely to be subjected to impaction from footwear. The direction of the force vector induced by this impaction may result in abduction of the hallux and adduction of the first metatarsal. It is possible that such deviation of the metatarsal may result in a medial collapse of the foot

and consequential lowering of the medial longitudinal arch. This may result in an increase in the hypermobility and modification of the forces acting upon the foot. Thus, the long hallux may contribute the destructive cycle of trauma-hypermobility-deformity that is assumed to result in hallux valgus. It seems likely that the magnitude and direction of the force vector induced by the impaction of the hallux on footwear is dependent on the type of footwear worn and that the degree of abduction of the hallux observed at the first metatarsophalangeal joint is dependent upon forces applied, in combination with the degree of hypermobility present in the foot. The magnitude of the impaction force and the degree of hypermobility may be increased by the type of footwear habitually worn by females. Thus, a greater potential for increased first metatarsophalangeal joint angle may exist among females. This could possibly account for the greater prevalence of hallux valgus observed among females.

Common to all of the predictors of hallux valgus identified in this study is that they appear to have the potential to affect the degree of hypermobility within the foot and/or the direction and magnitude of the forces acting on the foot. These two factors would seem, then, to be the key determinants of whether or not the first metatarsophalangeal joint angle remains within the normal limits or progresses beyond the abnormal threshold to become hallux valgus as clinically defined. As no direct measures of hypermobility or of the magnitude and direction of forces acting on the foot were made in this study, the accuracy of this observation is uncertain. Further research is required to identify the exact interactive role of these determinants in the development of hallux valgus. However, on the basis of the results of this study it seems likely that, as hypermobility and the forces acting on the foot increase, so too does the potential for hallux valgus. Since within this study hallux valgus was most commonly observed in individuals with an increased potential for both hypermobility and increased, detrimentally directed, forces acting on their feet. Specifically, hallux valgus was most commonly observed in females who have a positive family history of hallux valgus, planus feet, long, plantarflexed first rays and long hallux.

In the remainder of this chapter, the clinical implications of the study are discussed and implications and directions for future research are outlined.

6.3 Clinical Implications

It was demonstrated in Section 4.9 that, providing that the 95% confidence limits of prediction are observed and the limitations these place on the predicted values understood, the model presented in Section 4.8 provides the practitioner, for the first time, with a method of identifying individuals at risk of developing hallux valgus. Evaluation of the mean prediction and the 95% confidence intervals of the prediction allows the determination of an individual's risk of developing the deformity. By manipulation of the model the clinician may be given an insight into the prognosis of an individuals condition. However, the model developed within this study serves only as a clinical aid. It does not replace the need for a holistic viewpoint and sound clinical judgement when making decisions regarding the treatment of patients. To make a decision regarding treatment on the basis of the model's prediction in isolation would be foolish.

Given the prevalence of hallux valgus within the population, it is recommended that all patients attending podiatric clinics undergo the assessment described in chapter III and that their risk of developing hallux valgus is evaluated using the model presented in Equation 4.8. Even if a patient presents with severe hallux valgus, the examination and modelling process should be performed to allow prediction of progression and the monitoring of the condition, its predictors.

Ideally, individuals at risk of hallux valgus should be identified prior to the development of the deformity, since this may allow the implementation of prophylactic therapy. It is therefore recommended, that screening for the deformity, through the application of the assessment and model described in this study, should be carried out among children as part of any school foot health service.

Although predictor variables for hallux valgus have been identified by this study, causation and effect have not been delineated. At this time, therefore, manipulation of the model cannot, and should not, be used to simulate the effects of treatment. However, if through further research, causation is established, the model may then be applied to simulate the effects of hypothetical treatment regimes, prior to their instigation. This may conserve valuable resources and allow the most effective treatment to be instigated.

6.4 Implications for Further Research

This study has demonstrated that hallux valgus is multifactorial, with both genetic and environmental influences having a role in the development of the deformity. The study has also demonstrated that several predisposing factors- specifically arch height index, age, metatarsal formula, gender, first ray neutral position, family history and digital formula all contribute to the variance observed in first metatarsophalangeal joint angle and thus, hallux valgus. It is recommended, therefore, that the search for a single aetiological factor, which is responsible for hallux valgus, is fruitless. Future research should attempt to identify additional predictors of hallux valgus, with attention being given to their interactions and their mechanisms of hallux valgus formation.

Although the heritabilities of the foot measurement variables described in this study have been estimated, heritability is population specific and variable. It may be useful then, to obtain estimates for the variables from other populations, so that mean and 95% confidence interval values for the heritability estimates can be calculated and any trend with time (and possibly, footwear fashion) deduced. Clearly, it would also be advantageous to take heritability estimates for the variables from several different sorts of relatives, especially monozygotic (MZ) and dizygotic twins (DZ) and adopted, unrelated children living together. This may allow a clearer understanding of the roles of genetic and environmental influences in the variables. Moreover, by using age matched twin pairs, age adjustment of 1st MPJ angle and AHI data should not be required. Thus, the heritability estimates obtained would not be inflated by the shared environment components introduced by this process, and more accurate estimates of heritability should be obtained for these variables.

The predictors of 1st MPJ angle identified and used in this study accounted for 65% of the variance in 1st MPJ angle data. Clearly, a further 35% of the variance in 1st MPJ angle remains unexplained by the model. There are numerous other predisposing factors, in addition to those selected for use in this study, that have been proposed as significant in hallux valgus (Section 2.4). Further study and development of the model to include one or more of these factors in addition to those already included in the model may be useful. The addition of further predictor variables will inevitably result in an improvement in the fit of the model (r^2) and more of the variance in 1st MPJ angle should be accounted

for. By improving the fit of the model, the error in prediction and the 95% confidence limits of prediction should be reduced. Thus, the accuracy of the model could be improved by the addition of predictors. Given the findings of this study, an additional variable that relates to measurements of hypermobility within the foot may be a useful inclusion in any refined model. It should be noted, however, that the inclusion of too many variables in a refined model may limit its practical application, nullifying any improvement in its accuracy. All of the predictors selected in this study were chosen because they could be quickly and easily measured, using inexpensive instrumentation. If additional variables are to be used in refining the model, and the model is to maintain its practical application, these selection criteria should be adhered to. If practical application and expenditure are not limiting factors and a better academic understanding of hallux valgus and its predictors is all that is sought, then there is no limit to the number of predictors that could be included in the model. In these circumstances, more sophisticated measurement techniques may be applied to generate data, e.g. X-ray and magnetic resonance imaging (MRI). Using these techniques, variables that cannot be measured using simple clinical measurement techniques may be included in the model, e.g. metatarsus primus varus, height of intersesamoidal crista, metatarsal head shape.

The 95% confidence intervals of the predictions obtained using the model were relatively large. This may have been, in part, due to sampling error. Improved sampling techniques, specifically random sampling, may reduce variability in the measurements of the variables. This may allow the construction of an improved model with reduced 95% confidence intervals, thereby, providing better predictions of first metatarsophalangeal joint angle without the need for the inclusion of more predictor variables.

As previously stated (Section 6.3), although predictor variables for hallux valgus have been identified by this study, causation and effect have not been delineated. A longitudinal study design may help to provide an insight into which (if any) of the predictors are causative factors in hallux valgus and which are effects of the deformity. Identification of causative factors may allow the specific targeting of these factors in the treatment of the disorder, and may therefore allow improved prophylaxis. Moreover, once causation has been established, using this information the model may be refined and used to simulate the effects of hypothetical treatment regimes, prior to their instigation.

Prevention is said to be better than cure. In the case of hallux valgus, cure has commonly come in the form of reconstructive surgery, performed in the late stages of the condition, the outcome of which is variable. Although cause and effect between the predictor variable and hallux valgus has not yet been established, this study has provided a method of identifying individuals at risk of developing hallux valgus. This, in itself, may allow an earlier instigation of treatment for the condition, perhaps even prophylaxis. However, an effective prophylactic treatment for hallux valgus is yet to be identified. Given the findings of this study, in the search for an effective prophylactic and / or conservative treatment, research should address the fitting and design of shoes and the effects shoe designs have, not only on the foot, but on locomotion and body posture as a whole. Footwear modifications are already used in the treatment of many conditions. It may be possible to modify, or better still, to design and build a shoe actively to prevent hallux valgus. Clearly the "male" design of shoe appears to be better at this than the "female" design, but even this could be much improved upon. A shoe with a straight medial border may help to prevent the metatarsus primus varus component of hallux valgus. Close fitting heel counters, extended medially, can help to prevent abnormal pronation, as can medial heel flares or medial heel extensions (Thomas heel). Regardless of design, however, any shoe is of little use in the treatment of hallux valgus if the patient is not prepared to wear it because it is unfashionable. More work must be carried out in the area of foot health education to identify ways of changing the preconceptions and prejudices, not only of those at risk of developing hallux valgus, but more importantly of those responsible for the development of the patient's prejudices and the design of the shoes they wear: footwear manufacturers, shoe distributors and, principally, the fashion industry. When this is achieved the incidence of hallux valgus may be reduced.

APPENDICES

APPENDIX 1

This appendix contains a sample of the letter sent out to prospective subjects to assist in the generation of the study sample.

NORTHAMPTON SCHOOL of PODIATRY CLINIC CAMPUS

NORTHAMPTON GENERAL HOSPITAL,
CLIFTONVILLE,
NORTHAMPTON NN1 5DD

Tel: Northampton 27303
Northampton 34700 EX 5423

Head of School

Mrs L Merriman M.Phil, D.Pod M, M.Ch.S, Cert Ed.

Dear

A study is currently being undertaken into the inheritance of foot types within families in the Northampton area.The study requires the participation of a number of three and four generation families,i.e.Grandparents,parents,children (over six years old),from within the region.

The research is based around the measurement of bones and joints of the foot.The outcome of this is to provide greater understanding of the cause of foot problems and,therefore,improve in the treatment of such problems.

If you are a member of a three or four generation family,we should be grateful of your help by your participation in the study.This would require you and your family to attend the School of Podiatry on one occasion,however,arrangements can be made to visit members of your family at home if required.Treatment and advice will be provided if required.Confidentiality will be maintained at all times.

If you are interested in taking part in the study please contact me at the above telephone number,I look forward to hearing from you.

Yours sincerely,

S.K.Spooner

Research Assistant Northampton School of Podiatry

APPENDIX 2

A sample of the data collection sheet is provided within this appendix.

NAME.....

GENDER.....

AGE.....

PEDIGREE REF.....

	LEFT FOOT	RIGHT FOOT
1ST MPJ	.....	.....
FOOTPRINT	.....	.....
1ST RAY:		
DORSIFLEX	.....	.....
PLANTARFLEX.	.....	.....
NEUTRAL	.....	.....
MET FORM	.....	.....
DIG FORM	.....	.....

APPENDIX 3

This appendix contains the summary and analysis of variance statistics for the heritability analyses.

Summary and analysis of variance statistics. Linear regression of age adjusted male offspring on male parent first metatarsophalangeal joint angle.

Dependent Variable	Age adjusted 1st MPJ angle	Male offspring	Linear Regression
Multiple R	.59997		
R Square	.35996		
Adjusted R Square	.35575		
Standard Error	4.32776		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	1601.09784	1601.09784
Residuals	152	2846.88612	18.72951
F= 85.48529	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent 1st MPJ angle	.381898	.041305	.599967
Constant	11.643121	.784498	

Summary and analysis of variance statistics. Linear regression of age adjusted female offspring on male parent first metatarsophalangeal joint angle.

Dependent Variable	Age adjusted 1st MPJ angle	Female offspring	Linear Regression
Multiple R	.34848		
R Square	.12144		
Adjusted R Square	.11768		
Standard Error	5.96559		

	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	1151.04933	1151.04933
Residuals	234	8327.65214	35.58826
F= 32.34352	Significance of	F= .0000	

	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent 1st MPJ angle	.250672	.044077	.348476
Constant	18.159422	.859249	

Summary and analysis of variance statistics. Linear regression of age adjusted male offspring on female parent first metatarsophalangeal joint angle.

Dependent Variable	Age adjusted 1st MPJ angle	Male offspring	Linear Regression
Multiple R	.49329		
R Square	.24334		
Adjusted R Square	.24031		
Standard Error	4.15327		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	1386.83144	18886.83144
Residuals	250	4312.40547	17.24962
F= 80.39779	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent 1st MPJ angle	.303475	.033845	.493291
Constant	10.513483	.754859	

Summary and analysis of variance statistics. linear regression of age adjusted female offspring on female parent first metatarsophalangeal joint angle.

Dependent Variable	Age adjusted 1st MPJ angle	Male offspring	Linear Regression
Multiple R	.54642		
R Square	.29858		
Adjusted R Square	.29632		
Standard Error	5.77199		

	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	4410.53486	4410.53486
Residuals	311	10361.23047	33.31585
F= 132.38547	Significance of	F= .0000	

	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent 1st MPJ angle	.441464	.038368	.546424
Constant	13.053875	.873831	

Summary and analysis of variance statistics. Linear regression of age adjusted male offspring on male parent arch height index.

Dependent Variable	Age adjusted arch index	Male offspring	Linear Regression
Multiple R	.34624		
R Square	.11988		
Adjusted R Square	.11409		
Standard Error	.07458		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	.11517	.11517
Residuals	152	.84553	.00556
F= 20.70383	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent arch index	.219432	.048225	.346238
Constant	.482904	.030660	

Summary and analysis of variance statistics. Linear regression of age adjusted female offspring on male parent arch height index.

Dependent Variable	Age adjusted arch index	Female offspring	Linear Regression
Multiple R	.20972		
R Square	.04398		
Adjusted R Square	.03988		
Standard Error	.10211		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	.11176	.11176
Residuals	233	2.42934	.01043
F= 10.71904	Significance of	F= .0012	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent arch index	.204227	.062378	.209717
Constant	.607701	.039328	

Summary and analysis of variance statistics. Linear regression of age adjusted male offspring on female parent arch height index.

Dependent Variable	Age adjusted arch index	Male offspring	Linear Regression
Multiple R	.11284		
R Square	.01273		
Adjusted R Square	.00875		
Standard Error	.07778		

	Analysis of Variance		
	DF	Sum of Squares	Mean Square
Regression	1	.01935	.01935
Residuals	248	1.50047	.00605
F= 3.19862	Significance of F= .0749		

	Variables in the Equation		
Variable	B	SE B	Beta
Female Parent arch index	.050441	.028203	.112842
Constant	.585949	.020994	

Summary and analysis of variance statistics. Linear regression of age adjusted female offspring on female parent arch height index.

Dependent Variable	Age adjusted arch index	Female offspring	Linear Regression
Multiple R	.38428		
R Square	.14767		
Adjusted R Square	.14491		
Standard Error	.10008		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	.53619	.53619
Residuals	309	3.09476	.01002
F= 53.53692	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent arch index	.223635	.030564	.384282
Constant	.579160	.022521	

Summary and analysis of variance statistics. Linear regression of male offspring on male parent first ray neutral position.

Dependent Variable	1st ray position	Male offspring	Linear Regression
Multiple R	.25996		
R Square	.06758		
Adjusted R Square	.06145		
Standard Error	.51770		

	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	2.95260	2.95260
Residuals	152	40.73734	.26801
F= 11.01679	Significance of	F= .0011	

	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent 1st ray position	.230959	.069584	.259963
Constant	-.063906	.043161	

Summary and analysis of variance statistics. Linear regression of female offspring on male parent first ray neutral position.

Dependent Variable	1st ray position	Female offspring	Linear Regression
Multiple R	.20999		
R Square	.04410		
Adjusted R Square	.04001		
Standard Error	.59509		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	3.82274	3.82274
Residuals	234	82.86688	.35413
F= 10.79468	Significance of	F= .0012	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent 1st ray position	.210725	.064137	.209993
Constant	-.159751	.040746	

Summary and analysis of variance statistics. Linear regression of male offspring on female parent first ray neutral position.

Dependent Variable	1st ray position	Male offspring	Linear Regression
Multiple R	.25803		
R Square	.06658		
Adjusted R Square	.06285		
Standard Error	.55688		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	5.53001	5.53001
Residuals	250	77.52852	.31011
F= 17.83220	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent 1st ray position	.238481	.056474	.258030
Constant	-.031741	.037984	

Summary and analysis of variance statistics. Linear regression of male offspring on female parent first ray neutral position.

Dependent Variable	1st ray position	Male offspring	Linear Regression
Multiple R	.25803		
R Square	.06658		
Adjusted R Square	.06285		
Standard Error	.55688		

	Analysis of DF	Variance Sum of Squares	Mean Square
Regression	1	5.53001	5.53001
Residuals	250	77.52852	.31011
F= 17.83220	Significance of F= .0000		

	Variables in the Equation		
Variable	B	SE B	Beta
Female Parent 1st ray position	.238481	.056474	.258030
Constant	-.031741	.037984	

Summary and analysis of variance statistics. Linear regression of female offspring on female parent first ray neutral position.

Dependent Variable	1st ray position	Female offspring	Linear Regression
Multiple R	.28166		
R Square	.07933		
Adjusted R Square	.07640		
Standard Error	.58745		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	9.33713	9.33713
Residuals	314	108.36145	.34510
F= 27.05629	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent 1st ray position	.262772	.050518	.281657
Constant	-.063326	.036504	

Summary and analysis of variance statistics. Linear regression of male offspring on male parent metarsal formula dichotomous score.

Dependent Variable	Metatarsal formula	Male offspring	Linear Regression
Multiple R	.35593		
R Square	.12669		
Adjusted R Square	.12094		
Standard Error	.46996		

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	4.87013	4.87013
Residuals	152	33.57143	.22086
F= 22.05029	Significance of F= .0000		

Variables in the Equation

Variable	B	SE B	Beta
Male Parent metatarsal formula	.357143	.076056	.355934
Constant	.285714	.056171	

Summary and analysis of variance statistics. Linear regression of female offspring on male parent metarsal formula dichotomous score.

Dependent Variable	Metatarsal formula	Female offspring	Linear Regression
Multiple R	.30192		
R Square	.09115		
Adjusted R Square	.08727		
Standard Error	.44735		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	4.69669	4.69669
Residuals	234	46.82874	.20012
F= 23.46903	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent metatarsal formula	.282184	.058248	.301915
Constant	.534483	.041535	

Summary and analysis of variance statistics. Linear regression of male offspring on female parent metarsal formula dichotomous score.

Dependent Variable	Metatarsal formula	Male offspring	Linear Regression
Multiple R	.35634		
R Square	.12698		
Adjusted R Square	.12349		
Standard Error	.46891		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	7.99510	7.99510
Residuals	250	54.96919	.21988
F= 36.36173	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent metatarsal formula	.415844	.068962	.356340
Constant	.196721	.060038	

Summary and analysis of variance statistics. Linear regression of female offspring on female parent metarsal formula dichotomous score.

Dependent Variable	Metatarsal formula	Female offspring	Linear Regression
Multiple R	.45993		
R Square	.21153		
Adjusted R Square	.20900		
Standard Error	.42837		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	15.35964	15.35964
Residuals	312	57.25183	.18350
F= 83.70399	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent metatarsal formula	.471081	.051490	.459926
Constant	.320388	.042208	

Summary and analysis of variance statistics. Linear regression of male offspring on male parent digital formula dichotomous score.

Dependent Variable	Digital formula	Male offspring	Linear Regression
Multiple R	.48807		
R Square	.23822		
Adjusted R Square	.23327		
Standard Error	.43890		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	9.27668	9.27668
Residuals	154	29.66563	.19263
F= 48.15705	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent metatarsal formula	.487753	.070286	.488074
Constant	.233766	.050017	

Summary and analysis of variance statistics. Linear regression of female offspring on male parent digital formula dichotomous score.

Dependent Variable	Digital formula	Female offspring	Linear Regression
Multiple R	.32595		
R Square	.10624		
Adjusted R Square	.10240		
Standard Error	.47437		
	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	6.23246	6.23246
Residuals	233	52.43137	.22503
F= 27.69645	Significance of	F= .0000	
	Variables in	the Equation	
Variable	B	SE B	Beta
Male Parent metatarsal formula	.327877	.062302	.325945
Constant	.374046	.041446	

Summary and analysis of variance statistics. Linear regression of male offspring on female parent digital formula dichotomous score.

Dependent Variable	Digital formula	Male offspring	Linear Regression
Multiple R	.23656		
R Square	.05596		
Adjusted R Square	.05221		
Standard Error	.48676		

	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	3.53933	3.53933
Residuals	252	59.70871	.23694
F= 14.93769	Significance of	F= .0001	

	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent metatarsal formula	.243959	.063121	.236558
Constant	.315789	.049941	

Summary and analysis of variance statistics. Linear regression of female offspring on female parent digital formula dichotomous score.

Dependent Variable	Digital formula	Female offspring	Linear Regression
Multiple R	.34184		
R Square	.11686		
Adjusted R Square	.11401		
Standard Error	.46788		

	Analysis of	Variance	
	DF	Sum of Squares	Mean Square
Regression	1	8.97970	8.97970
Residuals	310	67.86325	.21891
F= 41.01936	Significance of	F= .0000	

	Variables in	the Equation	
Variable	B	SE B	Beta
Female Parent metatarsal formula	.350427	.054715	.341845
Constant	.314880	.043256	

APPENDIX 4

Prior to modelling knowledge of the inter-relationships between the variables was sought. Inter-relationship models were developed using the curve-fit procedure. The full results of this procedure are provided in this appendix.

MODEL: MOD_2.

Independent: AGE

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
ARCH	LIN	.177	386	83.07	.000	.5062	.0030		
ARCH	QUA	.254	385	65.53	.000	.6186	-.0041	8.7E-05	
ARCH	CUB	.256	384	43.93	.000	.6485	-.0075	.0002	-7.E-07
DIGDICOT	LIN	.039	386	15.46	.000	.2733	.0052		
DIGDICOT	QUA	.040	385	7.95	.000	.3241	.0020	3.9E-05	
DIGDICOT	CUB	.047	384	6.26	.000	.0904	.0283	-.0007	5.7E-06
GENDER	LIN	.002	386	.65	.422	.3869	.0011		
GENDER	QUA	.016	385	3.06	.048	.5624	-.0100	.0001	
GENDER	CUB	.016	384	2.04	.107	.5797	-.0119	.0002	-4.E-07
HA	LIN	.363	386	220.35	.000	6.4724	.2478		
HA	QUA	.383	385	119.25	.000	9.7092	.0440	.0025	
HA	CUB	.408	384	88.40	.000	2.6524	.8387	-.0197	.0002
HISTORY	LIN	.020	386	7.76	.006	.7492	.0026		
HISTORY	QUA	.022	385	4.42	.013	.8052	-.0009	4.3E-05	
HISTORY	CUB	.025	384	3.31	.020	.6999	.0110	-.0003	2.6E-06
METDICOT	LIN	.017	386	6.83	.009	.4400	.0034		
METDICOT	QUA	.018	385	3.43	.033	.4553	.0025	1.2E-05	
METDICOT	CUB	.026	384	3.37	.019	.2048	.0307	-.0008	6.1E-06
RAY	LIN	.032	386	12.94	.000	.0095	-.0058		
RAY	QUA	.037	385	7.43	.001	-.1170	.0022	-1.E-04	
RAY	CUB	.047	384	6.29	.000	.2204	-.0358	.0010	-8.E-06

MODEL: MOD_3.

Independent: ARCH

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
DIGDICOT	LIN	.019	386	7.67	.006	.1516	.5151		
DIGDICOT	QUA	.023	385	4.54	.011	-.3310	1.8843	-.9106	
DIGDICOT	CUB	.026	384	3.48	.016	1.2961	-5.0724	8.5619	-4.0714
GENDER	LIN	.038	386	15.31	.000	.8718	-.7145		
GENDER	QUA	.041	385	8.24	.000	.4397	.5117	-.8155	
GENDER	CUB	.046	384	6.15	.000	-1.4586	8.6281	-11.867	4.7501
HA	LIN	.404	386	261.92	.000	-6.8107	36.7173		
HA	QUA	.416	385	137.04	.000	6.7986	-1.8973	25.6801	
HA	CUB	.450	384	104.83	.000	87.3092	-346.12	494.393	-201.46
HISTORY	LIN	.021	386	8.28	.004	.6132	.3820		
HISTORY	QUA	.023	385	4.48	.012	.3711	1.0688	-.4568	
HISTORY	CUB	.023	384	3.01	.030	.0804	2.3117	-2.1491	.7274
METDICOT	LIN	.062	386	25.32	.000	.0082	.9076		
METDICOT	QUA	.073	385	15.18	.000	-.8514	3.3465	-1.6220	
METDICOT	CUB	.076	384	10.49	.000	.5692	-2.7273	6.6484	-3.5547
RAY	LIN	.075	386	31.27	.000	.5570	-1.2406		
RAY	QUA	.075	385	15.64	.000	.4219	-.8574	-.2549	
RAY	CUB	.093	384	13.11	.000	-4.1217	18.5689	-26.707	11.3692
AGE	LIN	.177	386	83.07	.000	1.7322	59.1121		
AGE	QUA	.177	385	41.44	.000	4.2597	51.9404	4.7694	
AGE	CUB	.194	384	30.79	.000	140.924	-532.37	800.395	-341.97

MODEL: MOD_4.

Independent: DIGDICOT

	Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
	GENDER	LIN	.019	386	7.57	.006	.4927	-.1375		
9	GENDER	QUA	.019	386	7.57	.006	.4927	-.1375		
9	GENDER	CUB	.019	386	7.57	.006	.4927	-.1375		
	HA	LIN	.083	386	34.80	.000	13.8829	4.4996		
9	HA	QUA	.083	386	34.80	.000	13.8829	4.4996		
9	HA	CUB	.083	386	34.80	.000	13.8829	4.4996		
	HISTORY	LIN	.056	386	22.94	.000	.7707	.1692		
9	HISTORY	QUA	.056	386	22.94	.000	.7707	.1692		
9	HISTORY	CUB	.056	386	22.94	.000	.7707	.1692		
	METDICOT	LIN	.223	386	111.04	.000	.3512	.4685		
9	METDICOT	QUA	.223	386	111.04	.000	.3512	.4685		
9	METDICOT	CUB	.223	386	111.04	.000	.3512	.4685		
	RAY	LIN	.021	386	8.43	.004	-.1293	-.1795		
9	RAY	QUA	.021	386	8.43	.004	-.1293	-.1795		
9	RAY	CUB	.021	386	8.43	.004	-.1293	-.1795		
	AGE	LIN	.039	386	15.46	.000	34.9415	7.4684		
9	AGE	QUA	.039	386	15.46	.000	34.9415	7.4684		
9	AGE	CUB	.039	386	15.46	.000	34.9415	7.4684		
	ARCH	LIN	.019	386	7.67	.006	.6036	.0378		
9	ARCH	QUA	.019	386	7.67	.006	.6036	.0378		
9	ARCH	CUB	.019	386	7.67	.006	.6036	.0378		

Notes:
9 Tolerance limits reached; some dependent variables were not entered.

MODEL: MOD_5.

Independent: GENDER

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
HA	LIN	.071	386	29.72	.000	17.8108	-4.2204		
9 HA	QUA	.071	386	29.72	.000	17.8108		-4.2204	
9 HA	CUB	.071	386	29.72	.000	17.8108			-4.2204
HISTORY	LIN	.000	386	.12	.734	.8559	-.0125		
9 HISTORY	QUA	.000	386	.12	.734	.8559		-.0125	
9 HISTORY	CUB	.000	386	.12	.734	.8559			-.0125
METDICOT	LIN	.069	386	28.68	.000	.6847	-.2630		
9 METDICOT	QUA	.069	386	28.68	.000	.6847		-.2630	
9 METDICOT	CUB	.069	386	28.68	.000	.6847			-.2630
RAY	LIN	.016	386	6.39	.012	-.2815	.1580		
9 RAY	QUA	.016	386	6.39	.012	-.2815		.1580	
9 RAY	CUB	.016	386	6.39	.012	-.2815			.1580
AGE	LIN	.002	386	.65	.422	37.7928	1.5687		
9 AGE	QUA	.002	386	.65	.422	37.7928		1.5687	
9 AGE	CUB	.002	386	.65	.422	37.7928			1.5687
ARCH	LIN	.038	386	15.31	.000	.6442	-.0534		
9 ARCH	QUA	.038	386	15.31	.000	.6442		-.0534	
9 ARCH	CUB	.038	386	15.31	.000	.6442			-.0534
DIGDICOT	LIN	.019	386	7.57	.006	.5315	-.1400		
9 DIGDICOT	QUA	.019	386	7.57	.006	.5315		-.1400	
9 DIGDICOT	CUB	.019	386	7.57	.006	.5315			-.1400

Notes:
9 Tolerance limits reached; some dependent variables were not entered.

MODEL: MOD_6.

Independent: HA

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
HISTORY	LIN	.088	386	37.19	.000	.6339	.0135		
HISTORY	QUA	.126	385	27.75	.000	.3784	.0417	-.0006	
HISTORY	CUB	.126	384	18.46	.000	.3878	.0401	-.0005	-1.E-06
METDICOT	LIN	.155	386	70.97	.000	.1726	.0250		
METDICOT	QUA	.221	385	54.76	.000	-.2944	.0765	-.0011	
METDICOT	CUB	.221	384	36.41	.000	-.3074	.0788	-.0012	1.6E-06
RAY	LIN	.138	386	61.93	.000	.2531	-.0292		
RAY	QUA	.143	385	32.24	.000	.4154	-.0471	.0004	
RAY	CUB	.165	384	25.29	.000	-.0549	.0372	-.0038	5.6E-05
AGE	LIN	.363	386	220.35	.000	14.9951	1.4663		
AGE	QUA	.376	385	116.17	.000	7.0629	2.3419	-.0192	
AGE	CUB	.380	384	78.35	.000	1.3133	3.3724	-.0702	.0007
ARCH	LIN	.404	386	261.92	.000	.4452	.0110		
ARCH	QUA	.437	385	149.30	.000	.5347	.0011	.0002	
ARCH	CUB	.523	384	140.37	.000	.7425	-.0361	.0021	-2.E-05
DIGDICOT	LIN	.083	386	34.80	.000	.1774	.0184		
DIGDICOT	QUA	.107	385	23.06	.000	-.1080	.0499	-.0007	
DIGDICOT	CUB	.107	384	15.40	.000	-.1611	.0594	-.0012	6.4E-06
GENDER	LIN	.071	386	29.72	.000	.6989	-.0169		
GENDER	QUA	.110	385	23.72	.000	1.0538	-.0561	.0009	
GENDER	CUB	.110	384	15.77	.000	1.0588	-.0570	.0009	-6.E-07

MODEL: MOD_7.

Independent: HISTORY

	Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
	METDICOT	LIN	.096	386	40.89	.000	.2069	.4295		
9	METDICOT	QUA	.096	386	40.89	.000	.2069		.4295	
9	METDICOT	CUB	.096	386	40.89	.000	.2069			.4295
	RAY	LIN	.021	386	8.45	.004	-4.E-16	-.2515		
9	RAY	QUA	.021	386	8.45	.004	-4.E-16	-.2515		
9	RAY	CUB	.021	386	8.45	.004	-4.E-16	-.2515		
	AGE	LIN	.020	386	7.76	.006	32.1034	7.4784		
9	AGE	QUA	.020	386	7.76	.006	32.1034	7.4784		
9	AGE	CUB	.020	386	7.76	.006	32.1034	7.4784		
	ARCH	LIN	.021	386	8.28	.004	.5747	.0550		
9	ARCH	QUA	.021	386	8.28	.004	.5747		.0550	
9	ARCH	CUB	.021	386	8.28	.004	.5747			.0550
	DIGDICOT	LIN	.056	386	22.94	.000	.1897	.3316		
9	DIGDICOT	QUA	.056	386	22.94	.000	.1897		.3316	
9	DIGDICOT	CUB	.056	386	22.94	.000	.1897			.3316
	GENDER	LIN	.000	386	.12	.734	.4483	-.0240		
9	GENDER	QUA	.000	386	.12	.734	.4483		-.0240	
9	GENDER	CUB	.000	386	.12	.734	.4483			-.0240
	HA	LIN	.088	386	37.19	.000	10.4828	6.4930		
9	HA	QUA	.088	386	37.19	.000	10.4828	6.4930		
9	HA	CUB	.088	386	37.19	.000	10.4828	6.4930		

Notes:
9 Tolerance limits reached; some dependent variables were not entered.

MODEL: MOD_8.

Independent: METDICOT

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
RAY	LIN	.065	386	26.86	.000	-.0331	-.3160		
9 RAY	QUA	.065	386	26.86	.000	-.0331	-.3160		
9 RAY	CUB	.065	386	26.86	.000	-.0331	-.3160		
AGE	LIN	.017	386	6.83	.009	35.5663	5.0644		
9 AGE	QUA	.017	386	6.83	.009	35.5663	5.0644		
9 AGE	CUB	.017	386	6.83	.009	35.5663	5.0644		
ARCH	LIN	.062	386	25.32	.000	.5826	.0678		
9 ARCH	QUA	.062	386	25.32	.000	.5826	.0678		
9 ARCH	CUB	.062	386	25.32	.000	.5826	.0678		
DIGDICOT	LIN	.223	386	111.04	.000	.1988	.4769		
9 DIGDICOT	QUA	.223	386	111.04	.000	.1988	.4769		
9 DIGDICOT	CUB	.223	386	111.04	.000	.1988	.4769		
GENDER	LIN	.069	386	28.68	.000	.5783	-.2630		
9 GENDER	QUA	.069	386	28.68	.000	.5783	-.2630		
9 GENDER	CUB	.069	386	28.68	.000	.5783	-.2630		
HA	LIN	.155	386	70.97	.000	12.4458	6.2209		
9 HA	QUA	.155	386	70.97	.000	12.4458	6.2209		
9 HA	CUB	.155	386	70.97	.000	12.4458	6.2209		
HISTORY	LIN	.096	386	40.89	.000	.7229	.2231		
9 HISTORY	QUA	.096	386	40.89	.000	.7229	.2231		
9 HISTORY	CUB	.096	386	40.89	.000	.7229	.2231		

Notes:
9 Tolerance limits reached; some dependent variables were not entered.

MODEL: MOD_9.

Independent: RAY

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2	b3
AGE	LIN	.032	386	12.94	.000	37.2699	-5.5816		
AGE	QUA	.058	385	11.75	.000	35.4887	-2.8319	5.6229	
AGE	CUB	.059	384	8.03	.000	35.1479	-4.0997	6.6638	1.3478
ARCH	LIN	.075	386	31.27	.000	.6085	-.0604		
ARCH	QUA	.084	385	17.61	.000	.6009	-.0488	.0238	
ARCH	CUB	.084	384	11.77	.000	.5997	-.0536	.0277	.0051
DIGDICOT	LIN	.021	386	8.43	.004	.4462	-.1191		
DIGDICOT	QUA	.021	385	4.23	.015	.4429	-.1140	.0103	
DIGDICOT	CUB	.028	384	3.74	.011	.4237	-.1854	.0690	.0759
GENDER	LIN	.016	386	6.39	.012	.4499	.1030		
GENDER	QUA	.018	385	3.44	.033	.4395	.1190	.0328	
GENDER	CUB	.018	384	2.31	.076	.4426	.1304	.0234	-.0121
HA	LIN	.138	386	61.93	.000	14.9916	-4.7382		
HA	QUA	.166	385	38.25	.000	14.2249	-3.5546	2.4203	
HA	CUB	.173	384	26.83	.000	13.9102	-4.7252	3.3814	1.2444
HISTORY	LIN	.021	386	8.45	.004	.8323	-.0851		
HISTORY	QUA	.029	385	5.71	.004	.8141	-.0571	.0574	
HISTORY	CUB	.033	384	4.32	.005	.8039	-.0950	.0885	.0403
METDICOT	LIN	.065	386	26.86	.000	.5281	-.2059		
METDICOT	QUA	.074	385	15.31	.000	.5010	-.1640	.0857	
METDICOT	CUB	.086	384	12.11	.000	.4750	-.2606	.1650	.1027

REFERENCES

REFERENCES

Adams, J.C., Hamblen, D.L.: Outline of orthopaedics (11th ed). *Edinburgh- Churchill Livingstone 1990*

Apley, A.G., Solomon, L.: Apley's system of orthopaedics and fractures (6th ed). London- Butterworth and Co. 1982

Barnicot, N.A., Hardy, R.H.: The position of the hallux in West Africans. J Anat 1955; **89**: 355-361

Bird, H.A.: Joint laxity. In Rheumatic Diseases: collected reports 1959-1983. The Arthritis and Rheumatism Council for Research 1983

Bonney, G., Macnab, I.: Hallux valgus and hallux rigidus. A critical survey of operative results. J Bone Joint Surg 1952; **34B**: 366-385

Bouysset, M., Tebib, J., Noel, E., Nemoz, C., Larbre, J.P., Bouvier, M.: Rheumatoid metatarsus. The original evolution of the first metatarsal. Clinical Rheumatology 1991; **10**: 408-412

Brahm, S.M.: Shape of the first metatarsal head in hallux rigidus and hallux valgus. JAPMA 1988; **78**: 300-304

Brodie, B.S., Rees, C.L., Robins, D.J., Wilson, A.F.J.: Wessex feet: a regional foot health survey. The Chiropodist 1988; **43**: 152-165

Cailliet, R.: Foot and ankle pain (2nd ed.). Philadelphia- F.A. Davies 1983

Carl, A., Ross, S., Evanski, P., Waugh, T.: Hypermobility in hallux valgus. Foot and Ankle 1988; **8**: 264-270

Carr, C.R., Boyd, B.M.: Correctional osteotomy for metatarsus primus varus and hallux valgus. J Bone Joint Surg 1968; **50B**: 1353-1367

Cavanagh, P.R., Rodgers, M.M.: The arch index: a useful measure from footprints. J Biomech 1987; **20**: 547-541

Clarke, H.H.: An objective method of measuring the height of the longitudinal arch in foot examinations. Res Q 1933; **4**: 99-107

Clough, J.G., Marshall, H.J.: The etiology of hallux valgus: a review of the literature. JAPMA 1985; **75**: 238-243

Cobey, J.C., Sella, E.: Standardizing methods of measurement of foot shape by including the effects of subtalar rotation. Foot and Ankle 1981; **2**: 30-36

Cohen, J.: Statistical power analysis for the behavioral sciences. New York- Academic Press 1977

Conlan, D., Gregg, P.J.: Treatment of hallux valgus with overiding second toe. J Bone Joint Surg 1991; **73B**: 519-520

Coughlin, M.J.: Juvenile hallux valgus: etiology and treatment. Foot and Ankle International 1995; **16**: 682-697

Cowell, H.R.: The genetics of foot disorders. Orthopaedic Review 1978; **7**: 55-58

Craigmile, D.A.: Incidence, origin and prevention of certain foot defects. B.M.J. 1953; **Oct**: 749-752

Cummings, M.R.: Human heredity: principles and issues (3rd ed). St. Paul- West Publishing Co. 1993

Cureton, T.K., Wickens, J.S., Haskell, P.E.: The validity of footprints as a measure of vertical height of the arch and functional efficiency of the foot. Res Q 1935; **6**: 70-80

Cyriax, J.H.: Textbook of orthopaedic medicine (8th ed). London- Bailliere and Tindall 1985

Cyriax, J.H., Cyriax, P.J.: Cyriax's illustrated manual of orthopaedic medicine (2nd ed). Oxford- Butterworth and Heinemann 1993

D'Amico, J.C., Schuster, R.O.: Motion of the first ray, clarification through investigation. JAPA 1974; **69**: 17-23

Dandy, D.J.: Essential orthopaedics and traumatology. Edinburgh- Churchill Livingstone 1989

Davidson, D.M.: The length of the lateral malleolus and pronation. JAPA 1970; **60**: 267-270

DeValentine, S.J.: Foot and ankle disorders in children. New York- Churchill Livingstone 1992

Didia, B.C., Nyenwe, B.: Foot breadth in children- its relationship to limb dominance and age. Foot and Ankle 1988; **8**: 198-202

Duckworth, T.: Lecture notes on orthopaedics and fractures (2nd ed). Oxford- Blackwell Scientific, 1984

Duckworth, T.: Painful conditions of the ankle and foot. The Practitioner 1985; **229**: 153-161

Duke, H., Newman, L.M., Bruskoff, B.L., Daniels, R: Relative metatarsal length patterns in hallux abducto valgus. JAPA 1982; **72**: 1-5

Durlacher, L.A.: A treatise on corns, bunions and diseases of the nails and general management of the feet. London- Simkin, Marshall & Co. 1845

DuVries, H.: DuVries' surgery of the foot (3rd ed), V.T. Inman (Ed), St. Louis -C.V. Mosby Co. 1973

Ebisui, J.M.: The first ray axis and the first metatarsophalangeal joint. JAPA 1968; **58**: 160-168

Elveru, R.A., Rothstein, J.M., Lamb, R.R.: Goniometric reliability in a clinical setting. Phys Ther 1988; **68**: 672-677

Falconer, D.S.: Introduction to quantitative genetics (3rd Ed). Longman Scientific and Technical 1989

Fitzgerald, J.A.W.: A review of long-term results of arthrodesis of the first metatarso-phalangeal joint. J Bone Joint Surg 1969; **51B**: 488-493

Fox, H.R., Firshein, D.B.: Variation in practitioner-measured X-ray angles in hallux abducto valgus evaluation. J Foot Surg 1989; **28**: 33-37

Freeman, A.C.: A study of the inter-tester and intra-tester reliability in the measurement of resting calcaneal stance position and neutral calcaneal stance position. Australian Podiatrist 1990; **June**: 10-13

Galton, F.: Natural Inheritance. London- Macmillan 1889

Gastwirth, B.W., O'Brien, T.D., Nelson, R.M., Manger, D.C., Kindig, S.A.: An electrodynographic study of foot function in shoes of varying heel heights. JAPMA 1991; **81**: 463-472

Gibson, J., Piggott, H.: Osteotomy of the neck of the first metatarsal in the treatment of hallux valgus. J Bone Joint Surg 1962; **44B**: 349-355

Gilmore, G.H., Bush, L.F.: Hallux valgus. Surgery, Gynecology and Obstetrics 1957; **May**: 524-528

Glynn, M., Dunlop, J., Fitzpatrick, D.: The Mitchell distal metatarsal osteotomy for hallux valgus. J Bone Joint Surg 1980; **62B**: 188-191

Goldner, J.L., Gaines, R.W.: Adult and juvenile hallux valgus: analysis and treatment. Orthop Clin North Am 1976; 7: 863-865

Goldthwaite, J.E.: The treatment of hallux valgus. Boston Med Surg J 1893; **129**: 533-535

Gottshalk, F.A.B., Beighton, P.H., Solomon, L.: The prevalence of hallux valgus in three South African populations. SA Medical Journal 1981; **60**: 655-656

Greenberg, F., Horowitz, I., Shangold, J., Skliar, J.D.: A report of foot examinations of school children. JAPMA 1963; **53**: 508-509

Greenberg, G.S.: Relationship of hallux abductus angle and first metatarsal angle to severity of pronation. JAPA 1979; **69**: 29-34

Grode, S.E., McCarthy, D.J.: The anatomical implications of hallux abducto valgus. JAPA 1980; **70**: 539-551

Groiso, J.A.: Juvenile hallux valgus: a conservative approach to treatment. J Bone Joint Surg 1992; **74A**: 1367-1374

Hamill, J., Bates B.T., Knutzen, K.M., Kirkpatrick, G.M.: Relationship between selected static and dynamic lower extremity measures. Clinical Biomechanics 1989; **4**: 217-225

Hardy, R.H., Clapham J.C.R.: Observations on hallux valgus based on a controlled series. J Bone Joint Surg 1951; **33B**: 376-391

Harris, N.H.: Post-graduate textbook of orthopaedics. Bristol- Wright PSG 1983

Harris, R.I., Beath, T.: Army foot survey: an investigation of foot ailments in Canadian soldiers. Ottawa, National Research Council of Canada 1947

Hawes, M.R., Nachbauer, W., Sovak, P., Nat, S., Nigg, B.: Footprint parameters as a measure of arch height. Foot and Ankle 1992; **13**: 22-26

Hawes, M.R., Sovak, D., Miyashita, M., Kang, S., Yoshihuku, Y. Tanaka, S.: Ethnic differences in forefoot shape and the determination of shoe comfort. Ergonomics 1994; **37**: 187-196

Hawkins, F., Mitchell, C., Hedrick, D.: Correction of hallux valgus by metatarsal osteotomy. J Bone Joint Surg 1945; **27B**: 387-394

Heden, R.I., Sorto, L.A.: The buckle point and the metatarsal protrusion's relationship to hallux valgus. JAPA 1981; 71: 200-207

Helal B., Wilson D.: The foot (Vol I). Edinburgh- Churchill Livingstone 1988

Heylings, D.J.A.: Hallux valgus and abductor hallucis personal thoughts on their connection. The chiropodist 1990; 45: 162-164

Hicks, J.H.: The mechanics of the foot. I. The joints. J Anatomy 1953; 87: 345-357

Hicks, J.H.: The mechanics of the foot. II. The plantar aponeurosis and the arch. J Anatomy 1954; 88: 25-30

Hoffman, P.: Conclusions drawn from a comparative study of the feet of barefooted and shoe-wearing peoples. Am J Orthop Surg 1905; 3: 107

Hughes, J.: Footwear and footcare for disabled children. London- Disabled Living Foundation 1982

Hughes, J.: Footwear and footcare for adults. London- Disabled Living Foundation 1983

Iida, M., Basmajian, J.V.: Electromyography of hallux valgus. Clin Orthop 1974; 101: 200-224

Inman, V.T.: Hallux valgus; a review of etiologic factors. Orthop Clin North Am 1974; 5: 59-66

Irwin, L.W.: A study of the tendency of school children to develop flat-footedness. Res Q 1937; 8: 46-53

Isman, R.E., Inman, V.T.: Anthropometric studies of the human foot and ankle. Bull Prosthet Res 1969; 11: 97

James, C.S.: Footprints and feet of natives of the Solomon Islands. Lancet 1939; 2: 1391

Janis, L.R., Donick, I.: The aetiology of hallux varus: a review. JAPA 1975; 65: 233-237

Johnston, O.: Further studies of the inheritance of hand and foot anomolies. Clin Orthop 1956; 8: 146-159

Jordon, H.H., Brodsky, A.E.: Keller operation for hallux valgus and hallux rigidus. Am Arch Surg 1951; 62: 586-596

Kalen, V., Brecher, A.: Relationship between adolescent bunions and flatfeet. Foot and Ankle 1988; 8: 331-336

Kelikian, H.: Hallux valgus. Allied deformities of the forefoot and metatarsalgia. Philadelphia- Saunders 1965

Kelso, S.F., Richie, D.H., Cohen, I.R., Weed, J.H., Root, M.: Direction and range of motion of the first ray. JAPA 1982; 72: 600-605

Kilmartin, T.E., Bishop, A.: Hallux abductus angle measurement: repeatability trials of a clinical measuring instrument. The Chiropodist 1988; 43: 185-187

Kilmartin, T.E., Wallace W.A.: A model for foot health screening. British Journal of Podiatric Medicine and Surgery 1990; 2: 8-10

Kilmartin, T.E., Wallace W.A.: Podiatric screening for abnormalities predisposing to juvenile foot deformity. The Chiropodist 1990; **45**: 205-207

Kilmartin, T.E., Barrington, R.L., Wallace, W.A.: Metatarsus primus varus- a statistical study. J Bone Joint Surg 1991; **73B**: 937-940

Kilmartin, T.E., Wallace, W.A., Hill, T.W.: First metatarsal position in juvenile hallux abducto valgus- a significant clinical measurement? JBPM 1991; 46: 43-45

Kilmartin, T.E.: But you haven't proved that orthoses work. Search News 1991; March: 8-11

Kilmartin, T.E., Wallace, W.A.: Significance of pes planus in juvenile hallux valgus. Foot and Ankle 1992; **13**: 53-56

Kilmartin, T.E., Wallace, W.A.: The aetiology of hallux valgus: a critical review of the literature. The Foot 1993; **3**: 157-167

Kilmartin, T.E., Barrington, R.L., Wallace, W.A.: A controlled prospective trial of foot orthosis for juvenile hallux valgus. J Bone Joint Surg 1994; **76B**: 210-214

Kirby, K.A.: Methods for determination of positional variations in the subtalar joint axis. JAPMA 1987; 77: 228-235

Klaue, K., Hansen, S.T, Masquelet, A.C.: Clinical, quantitative assesment of tarsometatarsal mobility in the sagittal plane and its relation to hallux valgus deformity. Foot and Ankle 1994; **15**: 9-13

Klenerman, L.: The foot and its disorders (2nd ed). Oxford- Blackwell Scientific 1982

Kolker, L.D.: A biomechanical analysis of flatfoot surgery. JAPA 1973; **63**: 217-236

Lake, N.C.: The foot (4th ed.) London- Bailliere, Tindall and Cox 1952

LaPorta, G., Melillo, T., Olinsky, D.: X-ray evaluation of hallux abducto valgus deformity. JAPA 1974; **64**: 544-566

Lattanza, L., Gray, G.W., Kantner, R.M.: Closed versus open kinetic chain measurements of calcaneal eversion: implications for clinical practice. J Orthopaedic Sports Phys Ther 1988; 9: 310-314

Lord, M., Hosein R., Williams, R.B.: Method for in-shoe shear stress measurement. J Biomed. Eng. 1992; **14**: 181-186

Love, T.R., Whynot, A.S., Farine, M.D.: Keller arthroplasty: a prospective review. Foot and Ankle 1987; **8**: 46-54

Maclennan, R.: Prevalence of hallux valgus in a neolithic New Guinea population. The Lancet 1966; **June**: 1398-1400

Magee, D.J.: Orthopaedic physical assesment. W.B. Saunders and Co. 1987

Mahan, K.T., Jacko, J.: Juvenile hallux valgus with compensated metatarsus adductus. JAPMA 1991; 10: 525-530

Mann, R.A.: Hallux valgus and complications of hallux valgus. In Mann, R.A. (Ed): Surgery of the Foot. St. Louis: Mosby, 1986

Mann, R.A., Rudicel, S., Graves, S.: Repair of hallux valgus with distal soft tissue procedure and proximal metatarsal osteotomy. J Bone Joint Surg 1992; 74A: 124-129

Manter, J.T.: Movement of the subtalar joint and transverse metatarsal joints. Anat Rec 1941; 80: 397-342

Marr, S.J., D'Abrera, H.J.M.: Survey of joint mobility and foot problems of 191 Australian children. JAPMA 1985; 75: 597-602

Maslen, B.A., Ackland, T.R.: Radiographic study of skin displacement errors in the foot and ankle during standing. Clin Biomech 1994; 9: 291-296

Mauldin, D.M., Sanders, M., Whitmer, W.W.: Correction for hallux valgus with metatarsocuneiform stabilisation. Foot and Ankle 1990; 11: 59-66

McBride, I.D., Wyss, U.P., Cooke, T.D.V., Murphy, L., Phillips, J., Olney, S.J.: First metatarsophalangeal joint reaction forces during high heel gait. Foot and Ankle 1991; 11: 282-288

McCarthy, D.J., Gessner, R.: Anatomical basis for congenital deformities of the lower extremities. Part 1. The hip and thigh. JAPMA 1993; 83: 18-28

Meier, P.J., Kenzora, J.E.: The risk and benefits of distal first metatarsal osteotomies. Foot and Ankle 1985; 6: 7-17

Menz, H.B.: Clinical hindfoot measurement: a critical review of the literature. The foot 1995; 5: 57-64

Merkel, K.D., Katoh, Y.: Mitchell osteotomy for hallux valgus: long term follow up and gait analysis. Foot and Ankle 1983; 3: 189-196

Merrill, H.E., Frankson, J. Tarara, E.L.: Podiatry survey of 1011 nursing home patients in Minnesota. JAPMA 1967; 57: 57-64

Meyer, M.: A comparison of hallux abducto valgus in two ancient populations. JAPA 1979; 69: 65-68

Miller, H.G.: Suggested aetiology of the abducted gait of pronation. JAPA 1960; 50: 388-389

Miller, M., Miller, J.H.: Orthopaedics and accidents illustrated. Oxford- Hodder and Stoughton Educational 1985

Mitchell, C.L., Fleming, J.L., Allen, R.: Osteotomy-bunionectomy for hallux valgus. J Bone Joint Surg 1958; 40A: 41-60

Morton, D.J.: Structural factors in static disorders of the foot. American Journal of Surgery 1930; IX: 315-329

Muckle, D.S.: Outline of orthopaedic practice. Bristol- John wright 1986

Neale, D., Hooper, G., Clowes, C.B., Whiting, M.F.: Adult foot disorders. In Neale, D., Adams, I. (Ed): Common Foot Disorders (2nd ed.). Churchill Livingstone, 1985

Nilsonne, H.: Hallux rigidus and its treatment. Acta Orthop Scand. 1930; 1: 295

Norusis, M.J.: SPSS for Windows: base system users guide. Release 6.0. SPSS Inc. 1993

O'Doherty, D.P., Lowrie, I.G., Magnussen, P.A.: The management of the painful first metatarsophalangeal joint in the older patient. J Bone Joint Surg 1990; **72B**: 839-842

Oldenbrook, L.L., Smith, C.E.: Metatarsal head motion secondary to rearfoot pronation and supination. JAPA 1974; **69**: 24-28

Osbourne, D., DeGeorge, M.: Genetic basis of morphological variation. Cambridge Mass-Harvard University Press 1959

Otman, S., Basgoze, O., Gokce-Kutsal, Y.: Energy cost of walking with flat feet. Prosthetics and Orthotics International 1988; **12**: 73-76

Page, J.C.: Symptomatic flatfoot: etiology and diagnosis. JAPMA 1983; **73**: 393-399

Paton, D.F.: Fractures and orthopaedics. Edinburgh- Churchill Livingstone 1988

Phillips, R.D., Reczek, D.M., Fountain, D., Renner, J., Park, D.B.: Modification of high-heeled shoes to decrease pronation during gait. JAPMA 1991; **81**: 215-219

Phillips, R.D., Lidtke, R.H.: Clinical determination of the linear equation for the subtalar joint axis. JAPMA 1992; **82**: 1-19

Piggott, H.: The natural history of hallux valgus in adolescents and early adult life. J Bone Joint Surg 1960; **42B**: 749-760

Plaster, H.M.: Hallux valgus as related to the first metatarsal length pattern. JAPA 1954; **44**: 17-23

Plomin, R., DeFries, J.C., McClearn, G.E.: Behavioral genetics: a primer (2nd ed). New York- W.H. Freeman and Co. 1990

Pressman, M.M.: Biomechanics and surgical criteria for flexible pes valgus. JAPMA 1987; 77: 7-13

Rao, U.B., Joseph, B.: The influence of footwear on the prevalence of flat foot. J Bone Joint Surg 1992; **74B**: 525-527

Riedel, H.: In Kelikian, H.: Hallux valgus. Allied deformities of the forefoot and metatarsalgia. Philadelphia: Saunders, 1965

Resch, S., Stenstrom, A., Egund, N.: Proximal closing wedge osteotomy and adductor tenotomy for the treatment of hallux valgus. Foot and Ankle 1989; 9: 272-280

Rodrigo, J.J.: Orthopaedic surgery: Basic science and clinical science. Boston- Little, Brown and Co. 1986

Rogers, W.A., Joplin R.J.: Hallux valgus, weak foot and the Keller operation. Surg Clin North Am 1947; 1295-1302

Root, M.L., Weed, J.H., Sgarlato, T.E.: Axis of motion of the subtalar joint, an anatomical study. JAPA 1966; **56**: 149-156

Root, M.L., Orien, W.P., Weed, J.H.: Biomechanical examination of the foot. Los Angeles- Clinical Biomechanics Corp. 1971

Root, M.L., Orien, W.P., Weed, J.H.: Normal and abnormal function of the foot, Vol II. Los Angeles-Clinical Biomechanics Corp. 1977

Ross, F.D.: The relationship of abnormal foot pronation to hallux abducto valgus- a pilot study. Prosthetics and Orthotics International 1986; 10: 72-78

Rothbart, B.A.: Metatarsus adductus and its clinical significance. JAPA 1972: 62: 187-191

Sabbann, R.: Children's foot examination at state fair. JAPMA 1965; 55: 439

Sanders, A.P., Snijders, C.J., Van Linge, B.: Medial deviation of the first metatarsal head as a result of flexion forces in hallux valgus. Foot and Ankle 1992; 13: 515-522

Saragas, N.P., Becker, P.J.: Comparative radiographic analysis of parameters in feet withh and without hallux valgus. Foot and Ankle 1995; 16: 139-143

Schnitzer, J.S., Hoeffler, D.F.: The distribution and etiology of foot disorders in a Navy recruit program. JAPMA 1974; 64: 845-853

Schuster, R.O., Port, M.: Abnormal pronation in children. An Hormonal etiology. JAPA 1977; 67: 613-615

Schwartz, L., Britten, R.H., Thompson, L.R.: Studies of physical development and posture, U.S. Public Health Bulletin No. 179. Washington DC, U.S. Government Printing Office 1928

Schwartz, R.P., Heath A.L.: Preliminary findings from a roentgenographic study of the influence of heel height and empirical shank curvature on osteo-articular relationships in the normal female foot. J Bone Joint Surg 1959; 41A: 1065-1076

Schwartz, R.P., Heath A.L., Morgan, D.W.: A quantitative analysis of recorded variables in the walking pattern for "normal" adults. J Bone Joint Surg 1964; 46A: 324-
Scranton, P.E.: Principles in bunion surgery. J Bone Joint Surg 1983; 65A: 1026-1028

Sherman, K.P., Douglas, D.L., D'A Benson, M.K.: Keller's arthroplasty: Is distraction useful? A prospective trial. J Bone Joint Surg 1984; 66B: 765-769

Sherreff, M.J., DiGiovanni, L., Bejjani, F.J., Hersh, A., Kummer, F.J.: A comparison of nonweight-bearing and weight-bearing radiographs of the foot. Foot and Ankle 1990; 10: 306-311

Shimanski, K., Takebe, K.: Investigation on the origin of hallux valgus by electromyographic analysis. Kobe J Med Sci 1981; 27: 139-158

Shine, I.B.: Incidence of hallux valgus in a partially shoe-wearing community. BMJ 1965; 1648-1650

Siebel, M.O.: Foot function: a programmed text. Baltimore- Williams and Wilkins 1988

Sim-Fook, L., Hodgson, A.R.: A comparison of foot forms among the non-shoe and shoe-wearing Chinese population. J Bone Joint Surg 1958; 40A: 1058-1062

Snijders, C.J., Snijder, J.G.N., Philippens, M.G.M.: Biomechanics of hallux valgus and spread foot. Foot and Ankle 1986; 7: 26-35

Soames R.W., Evans, A.A.: Female gait patterns: the influence of footwear. Ergonomics; 1987; 30: 893-

Staheli, L.T., Chew, D.E., Corbett, M.: The longitudinal arch. J Bone Joint Surg 1987; 69A: 426-428

Stamm, T.T.: Surgical treatment of hallux valgus. Guys Hospital Reports 1957; 106: 21-26

Stott, J.R.R., Hutton, W.C., Stokes, I.A.F.: Forces under the foot. J Bone Joint Surg 1973; 55B: 335-344

Sussman, R.E., D'Amico, J.C.: The influence of the height of the heel on the first metatarsophalangeal joint. JAPA 1984; 74: 504-508

Tachdjian, M.O.: The childs foot. Philadelphia- Saunders 1985

The Gallup Organisation Inc: Women's attitudes and usage of high heel shocs. August 1986

Thomson, C.E.: An investigation into the reliability of the valgus index and its validity as a clinical measurement. The Foot 1994; 4: 191-197

Thomson, P.: Embryology and the neonate. In Podopaediatrics (Ed) Thomson 1993- W.B. Saunders Company Ltd.

Thul, J.R., Stone, M.L., Gilarski, C.K.: Congenital hallux valgus occuring with the windswept deformity. JAPMA 1985; 10: 544-547

Turgut, H.B., Anil, A., Peker, T.V., Ulukent, S.C.: Incidence of long second toe among university students. The Foot 1997; 7: 30-32

Vallier, G.T., Peterson, S.A., LaGrone, M.: Keller resection arthroplasty: a 13 year experience. Foot and Ankle 1991; 11: 187-194

Wanivenhaus, A.H., Feldner Busztin, H.: Basal osteotomy of the first metatarsal for the correction of metatarsus primus varus associated with hallux valgus. Foot and Ankle 1988; 8: 337-343

Wanivenhaus, A.H., Pretterklieber, M.: First tarsometatarsal joint: anatomical biomechanical study. Foot and Ankle 1989; 9: 153-157

Welton, E.A.: The Harris and Beath footprint: interpretation and clinical value. Foot and Ankle 1992; 13: 462-468

Wu, K.K.: Mitchell bunionectomy: an analysis of four hundred and thirty personal cases. J Foot Surg 1987; 26: 277-292

BIBLIOGRAPHY

BIBLIOGRAPHY

Ball, P., Johnson, G.R.: Reliability of hindfoot goniometry when using a flexible electrogoniometer. Clin Biomech 1993; 8: 13-19

Baum, I., Spencer, A.M.: Limb dominance- its relationship to foot length. JAPA 1980; 70: 505-507

Betts, R.P., Franks, C.I., Duckworth, T., Burke, J.: Static and dynamic foot-pressure measurements in clinical orthopaedics. Medical and Biological Engineering and Computing 1980; Sept.: 674-684

Blomgren, M., Turan, I., Agadir, M.: Gait analysis in hallux valgus. J Foot Surg; 30: 70-71

Blumel, J., Eggers, G.W.N., Burke-Evans, E.: Eight cases of hereditary bilateral medial tibial torsion in four generations. J Bone Joint Surg 1957; 39A: 1198-1202

Bodine, K.G.: The subtalar joint and some related pathology. JAPA 1970; 60: 205-207

Bring, J.: A geometric approach to compare vtariatbles in a regression model. The American Statistician 1996; 50: 57-62

Carter, C.D.: Genetics in orthopaedics. J Bone Joint Surg 1961; 43B: 217-219

Cavanagh, P.R., Rodgers, M.M., Iiboshi, A.: Pressure distribution under symptom free feet during barefoot standing. Foot and Ankle 1987; 7: 262-276

Cook, A., Gorman, I., Morris, J.: Evaluation of the neutral position of the subtalar joint. JAPMA 1988; 78: 449-451

Cralley, J.C., McGonagle, W., Fitch, K.: The role of adductor hallucis in bunion deformity (part I). JAPA 1976; 66: 910-918

Cralley, J.C., McGonagle, W., Fitch, K.: The role of adductor hallucis in bunion deformity (part II). JAPA 1978; 68: 473-483

Demp, P.: A mathematical model for the study of metatarsal length patterns. JAPA 1964; 64: 107-110

DiGiovanni, J.E., Smith, S.D.: Normal biomechanics of the adult rearfoot. JAPA 1976; 76: 812-824

Durman, D.C.: Metatarsus primus varus and hallux valgus. Arch surg. 1957; 74: 128-135

Emery, A.E.H.: Elements of medical genetics (5th ed). Edinburgh- Churchill Livingstone 1979

Esberger, K.K., Hughes, S.T.: Nursing care of the aged. Norwalk- Appleton and Lange 1989

Feldman, M.H., Wile, M.Z.: An orthopaedic evaluation of 30 sets of identical twins. JAPA 1972; 62: 425-430

Forriol, F., Pascual, J.: Footprint analysis between three and seventeen years of age. Foot and Ankle 1990; 11: 101-104

Foulston, J., Lord, M., West, S.: Changes in plantar surface shape induced by corrective forefoot eversion. Clin Biomech 1990; 5: 229-235

Gore, S.M., Altman, D.G.: Statistics in practice. London- British Medical Association 1982

Gould, N., Moreland, M., Trevino, S., Alverez, R., et al.: Development of the child's arch. Foot and Ankle 1989; 9: 241-245

Gould, N., Moreland, M., Trevino, S., Alverez, R., et al.: Foot growth in children age one to five years. Foot and Ankle 1990; 10: 211-213

Green, J., D' Oliveira, M.: Methodology handbook (Social sciences: a second level course. Introduction to psychology). The Open University Press 1981

Grundy, M., Tosh, P.A., McLeish, R.D., Smidt, L.: An investigation of the centres of pressure under the foot while walking. J Bone Joint Surg 1975; **57B**: 98-103

Harper, M.C.: Posterior instability of the talus: An anatomic evaluation. Foot and Ankle 1989; **10**: 36-39

Harper, W.M.: Statistics (2nd ed). London- MacDonald and Evans 1971

Heilman, A.E., Braly, W.G., Bishop, J.O., Noble, P.C., Tullos, H.S.: An anatomic study of subtalar instability. Foot and Ankle 1990; **10**: 224-228

Hineser, W.F., Perlman, P.R.: Statistical evaluation of the lower extremities of identical twins. JAPA 1972; **62**: 375-388

Hirsch, B.E.: Structural biomechanics of the foot bones. JAPMA 1991; **81**: 338-343

Hlavac, H.F.: Compensated forefoot varus. JAPA 1970; **60**: 229-233

Hughes, J., Kriss, S., Klenerman, L.: A clinician's view of foot pressure: a comparison of three different methods of measurement. Foot and Ankle 1987; 7: 277-284

Hutt, C.: Males and Females. Penguin Education 1972

Kaufman, I.W., Nemiroff, J.: A physiological basis for lateral statbilization of the foot. JAPA 1962; **52**: 32-34

Kilmartin, T.E., Wallace, W.A., Hill, T.: Orthotic effect on first metatarsophalangeal joint extension. JAPMA 1991; **81**: 414-417

Kirby, K.A.: Rotational equilibrium across the subtalar joint axis. JAPMA 1989; **79**: 1-14
Lewis, L.L.: Podal propulsive hinge as a key to normal foot function. JAPA 1966; **56**: 103-110

Maldin, R.: Axial rotation of the hallux as a factor in hallux valgus. JAPA 1972; **62**: 85-93

Mann, R.A.: The great toe. Orthop Clin North Am 1989; **20**: 519-528

Matthews, D.E., Farewell, V.T.: Using and understanding medical statistics (3rd ed, revised). Karger 1996

Meade, J.C.: Juvenile pes valgo planus. JAPA 1962; **52**: 275-277

Milgrom, C., Giladi, M., Simkin, A., Stein, M., et al.: The normal range of subtalar inversion and eversion in young males as measured by three different techniques. Foot and Ankle 1985; **6**: 143-145

Mittleman, G.: Transverse plane abnormalities of the lower extremities: intoe and outtoe gait. JAPA 1971; 61: 1-7

Moore, E.: Heredity: mainly human. London- Chapman and Hall 1934

Netter, J., Wasserman, W., Whitmore, G.A.: Applied statistics (4th ed). Boston- Allyn and Bacon 1978

O'Brien, B.: "What are my chances Doctor?"- A review of clinical risks. London- Office of Health Economics 1986

Peller, S.: Quantitative research in human biology and medicine. Bristol- John Wright and Sons Ltd. 1967

Penrose, L.S.: Outline of human genetics. London- Heinemann 1959

Pepin, W.A.: Measurements of hip rotation and foot pronation and supination in school children. JAPA 1963; 53: 181-186

Pepin, W.A., Marchand, E.R.: Some anatomical and physiological relationships in the foot. JAPA 1964; 54: 169-177

Pepin, W.A., Lauritsen, W.H.: The genicular effects of the imbalanced foot. JAPA 1965; 55: 518-521

Phillips, R.D., Phillips, R.L.: Quantitative analysis of the locking position of the midtarsal joint. JAPA 1983; 73: 518-522

Phillips, R.D., Christeck, R, Phillips, R.L.: Clinical measurement of the axis of the subtalar joint. JAPMA 1985; 75: 119-131

Pollard, J.P., Le Quesne, L.P., Tappin, J.W.: Forces under the foot. J Biomed Eng 1983; 5: 37-40

Rega, R., Green, D.R.: The extensor hallucis longus and the flexor hallucis longus tendons in hallux abducto valgus. JAPA 1978; 68: 467-472

Robbins, H.M.: The unified forefoot. JAPA 1981; 71: 465-471

Robbins, H.M.: The unified forefoot. II. The relationship between hallux valgus and metatarsus primus varus. Journal of Foot Surgery 1983; 22: 320-324

Rose, G.K., Welton, E.A., Marshall, T.: The diagnosis of flat foot in the child. J Bone Joint Surg 1985; 67B: 71-78

Sgarlato, T.E.: The angle of gait. JAPA 1965; 55: 645-650

Shaw, A.H.: The biomechanics of hallux valgus in pronated feet. JAPA 1974; 64: 193-202

Silvino, N., Evanski, P.M., Waugh, T.R.: The Harris and Beath footprinting mat: diagnostic validity and clinical use. Clinical Orthopaedics and Related Research 1980; 45: 265-269

Smith, A.: The human pedigree. London- George Allen and Unwin Ltd 1975

Soames, R.W.: Foot pressure patterns during gait. J Biomed Eng 1985; 7: 120-126

Strocchi, R., Pasquale, V., Guizzardi, S., Govoni, P., et al.: Human Achilles tendon: Morphological and morphometric variations as a function of age. Foot and Ankle 1991; 12: 100-104

Subotnick, S.I.: Equinus deformity as it affects the forfoot. JAPA 1971; 61: 423-427

Swann, W., Williams, P.: Statistics guide (E206). The Open University Press 1984

Tidswell, M.E. (Ed): Cash's textbook of orthopaedics and rheumatology for physiotherapists (2nd ed). Mosby- Year Book Europe Ltd. 1992

Tortora, G.J., Grabowski, S.R.: Principles of anatomy and physiology (7th ed). Harper Collins College Publishers 1993

Wevers, O.T., Hearn, T.C., Hunter, G.A., Ala-Korpi, T.: Method for relating the centre of pressure locus during dynamic stance to anatomical structures of the foot. Clinical Biomechanics 1989; 4: 111-114

Wynne-Davies, R.: Family studies and the cause of congenital club foot. J Bone Joint Surg 1964; 46B: 445-463

Young, J.Z.: An introduction to the study of man. Oxford University Press 1974