School of Surgery and Pathology

Analysis of dynamic angle of gait and radiographic features in subjects with hallux valgus

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ABSTRACT

Hallux valgus (HV) is one of the most common foot deformities encountered in clinical practice. This complex deformity primarily affects the first metatarsophalangeal joint (MPJ), leading to altered foot structure and function. By virtue of the lateral displacement of the hallux on the first metatarsal, HV has the potential to influence adjacent joints of the foot. In doing so, function of the foot may be altered, and clinically this may result in abduction of the foot during the stance phase of gait. However the relationship between an abducted angle of gait (AOG) and HV has never been substantially examined. The purpose of this study is to investigate the relationship between HV and AOG, and determine if specific radiographic features are associated with the deformity or with a particular AOG. Such information would assist in understanding aetiological factors and the effects of intervention to treat the deformity.

In order to fulfill the purposes of the study, it was first necessary to establish the reliability of the measurements of AOG and radiographic variables. It was also important to determine whether a particular AOG was secondary to factors intrinsic or extrinsic to the foot, accomplished through examination of the radiographic rearfoot axis angle, which provided a measure of the amount of intrinsic rearfoot to forefoot abduction. Finally, foot structure, as measured by the inclination angle of the calcaneus (CIA), was compared to AOG.

The investigation involved a HV group consisting of 23 subjects with a mean age of 61.3 years, and a control group made up of 20 subjects with a mean age of 58.8 years, as determined by degree of hallux abductus angle (HAA). All

subjects provided AOG data via a methodology involving powdered footprints recorded on paper. Radiographic variables obtained from weight bearing films included calcaneal inclination angle (CIA), lateral intermetatarsal angle (LIMA), hallux abductus angle (HAA), first intermetatarsal angle (FIMA), first metatarsal protrusion distance (FMPD), lateral stressed dorsiflexion (LAT SD) of the first MPJ, and rearfoot to forefoot axis (RFA) angle.

Data was analysed using descriptive and inferential statistics, involving the use of Pearson’s product moment correlations, t-tests, and non-parametric analyses with and without tertile assessments, based on HAA threshold.

The results indicated AOG measured from powdered footprints was reliable, as were the radiographic variables (intra-rater reliability 0.93-0.95, inter-rater reliability 0.93). Subjects with HV, whether unilateral or bilateral, did not show any significant difference in their AOG when compared to the control group. A difference in AOG between left and right feet was found in subjects with bilateral HV, whereas control subjects showed no difference between sides. Furthermore, AOG was not associated with degree of the HV deformity. In subjects with unilateral HV, AOG did not differ between left and right feet.

Angle of gait did not reflect the amount of rearfoot to forefoot abduction in the HV foot when compared to controls, suggesting that perhaps extrinsic factors, such as foot dominance, leg length or the presence of symptoms may be important in determining AOG. Angle of gait did not appear to be influenced by architecture of the foot as measured by CIA.

Despite the finding that HV subjects did not have a long, short, or elevated first metatarsal when compared to the control group, a number of associations were found between radiographic variables. Length and elevation of the first metatarsal were associated in subjects with HV, implying that length of the metatarsal may be related to whether or not it becomes elevated (R: 0.50, CI: 0.21, 0.71, $P< 0.05$). Similarly, an association was found between length of the first metatarsal and the amount of first MPJ dorsiflexion, suggesting perhaps length of the metatarsal has implications for first MPJ range of motion (R: -0.37, CI: -0.62, -0.04, $P<0.05$). However the amount of first MPJ dorsiflexion did not influence the AOG in HV subjects when compared to the control group. First MPJ dorsiflexion was also associated with the first intermetatarsal angle. Interestingly, the HV group alone did not show an association between the hallux abductus angle and the first intermetatarsal angle.

The findings of this study are contrary to those suspected in clinical practice and alluded to in the literature. Despite the documented support for the biomechanical causes of HV, an abducted AOG was not significantly different in HV subjects when compared to controls. Possible explanations may have related to limitations of the present study including the size and gender demographics of the sample population, and greater variability in normal AOG ranges than reported in the literature. The present study indicated a possible need to gather information regarding foot dominance and leg length; factors extrinsic to the foot capable of influencing transverse plane orientation of the foot; and, the influence of symptoms and subsequent compensatory mechanisms adopted during gait.

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DECLARATION OF ORIGINALITY

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The pilot studies and final research study were developed in association with my thesis supervisors, who were also involved in editing both this thesis and associated publications. I have independently performed all the experimental work and analysis of results.

I declare that all material presented in this thesis is original, apart from the work from other sources which has been acknowledged within the text. Review of relevant literature to the thesis has been included up to July 2004.

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LIST OF ABBREVIATIONS

AOG:	Angle of gait
BMI:	Body mass index
CIA:	Calcaneal inclination angle
COMP:	Composite
DP:	Dorso-plantar
FIMA:	First intermetatarsal angle
FMPD:	First metatarsal protrusion distance
FPA:	Foot progression angle
HAA:	Hallux abductus angle
HAI:	Hallux abductus interphalangeus
HL:	Hallux limitus
HV:	Hallux valgus
LAT SD:	Lateral stressed dorsiflexion
LAT:	Lateral
LIMA:	Lateral intermetatarsal angle
MPJ:	Metatarsophalangeal joint
RFA ANGLE:	Rearfoot to forefoot axis angle

LIST OF PUBLICATIONS:

1. Taranto J, Taranto M, Bryant A, Singer K. Angle of gait: a comparative reliability study using footprints and the EMED-SF®. *The Foot.* 2004; Accepted for publication. (Appendix 1)

2. Taranto M, Taranto J, Bryant A, Singer K. A radiographic study investigating the reliability of first metatarsophalangeal joint dorsiflexion and rearfoot to forefoot axis angle using a lateral stressed dorsiflexion and composite view. *Journal of Foot and Ankle Surgery.* 2004; Accepted for publication. (Appendix 2)

CHAPTER ONE

DEVELOPMENT OF THE PROBLEM

1.0 Introduction

Hallux valgus (HV) is one of the most commonly seen foot deformities.[1, 2] Clinical observation of this deformity has suggested a potential relationship between the presence of the deformity and an abducted angle of gait (AOG) when walking. However, this relationship has never been substantially investigated. Furthermore, whether or not an abducted AOG is a precursor or a compensation of the HV deformity remains unknown. Investigation of this potential relationship is important in understanding aetiological pathomechanics and the effects of intervention to treat or correct the deformity.

Chapter One introduces the reader to the rationale behind the present investigation, highlighting the nature of the problem, purposes and significance of the study, assumptions, limitations, and relevant terminology, including specific radiographic variables measured. Research hypotheses are outlined and a summary of the Chapter is provided. More detailed description of radiographic angular measurements is provided in the methodology section (Chapter 3) of this thesis.

1.1 Statement of the problem and purpose of the study

Controversy exists in the literature regarding normal parameters for AOG. There is confusion as to whether an abducted AOG is considered pathological. Additionally, measurement of AOG in dynamic foot function has not been investigated in the presence of pathology. In light of this problem, the present investigation contains four main purposes.

Firstly, to investigate differences in the dynamic AOG between subjects with and without HV. Fulfillment of this purpose first requires establishment of reliability relating to measurement of AOG.

The second purpose is to determine whether the dynamic AOG is related to the amount of rearfoot to forefoot abduction within the foot. Consideration of the amount of rearfoot to forefoot abduction within the foot is important to determine whether abduction is a result of intrinsic or extrinsic factors. Intrinsic abduction of the foot, or the amount of rearfoot to forefoot abduction is measured radiographically by the rearfoot axis (RFA) angle[3] obtained from a composite (COMP) view.[4]

Thirdly, to measure first metatarsal radiographic features in HV as a means to understanding a possible relationship between degree of deformity or functional disability and dynamic AOG. This would investigate whether intrinsic radiographic findings were predictive of HV or a particular AOG. Specifically, these radiographic measurements were hallux abductus angle (HAA), first intermetatarsal angle (FIMA), first metatarsal protrusion distance (FMPD), lateral first intermetatarsal angle (LIMA), and degree of available first metatarsophalangeal joint (MPJ) dorsiflexion by measurement of lateral stressed dorsiflexion (LAT SD) of the first MPJ.

The final purpose is to determine whether AOG is related to foot type. Calcaneal inclination angle (CIA) is to be used as a measure of foot type, whereby a higher inclination angle reflects a higher arched foot than a lower inclination angle.[5]

In order to satisfy the purposes of the investigation based on radiographic parameters, it is first necessary to obtain reliability parameters for each radiographic variable. All radiographic variables are to be taken while weight bearing, thereby allowing a functional representation of the foot.

1.1.1 Angle of gait pilot study

The purpose of this pilot study[6] (Appendix 1) was to assess the reliability and comparability of two different techniques to quantify AOG. This was achieved by a two-part approach; the first assessed reliability of AOG derived from powdered footprints, and the second undertook a comparison between AOG from powdered footprints, and the equivalent measurement of AOG, known as foot progression angle (FPA), derived from the EMED-SF® (novel, gmbh, Munich, Germany) pressure platform (Figure 1.1).

1.1.2 Radiographic pilot study

The purpose of this pilot study[7] (Appendix 2) was to assess the reliability of seven angular and linear radiographic parameters to be used in the present investigation. Amongst these were two uncommon views, namely LAT SD of the first MPJ and the COMP view.

1.2 Significance of the study

The findings of this study will enable a better understanding of the deformity of HV and provide new insights into whether particular intrinsic radiographic features of the foot are predictors of AOG, and whether an abducted AOG is associated with HV.

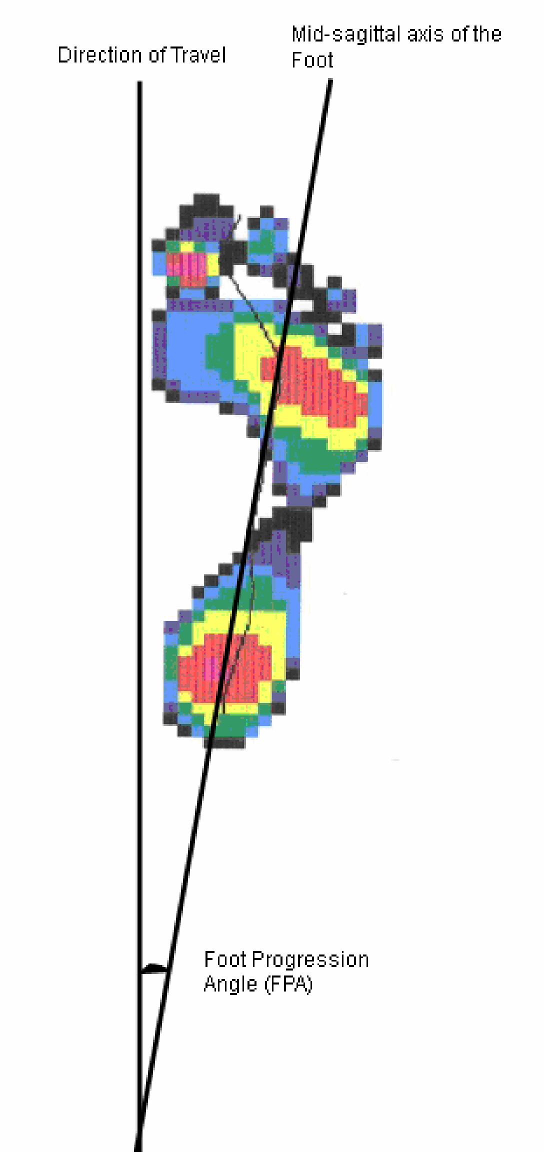

Figure 1.1: EMED-SF® maximum pressure image depicting FPA defined as the angle formed between the direction of travel and the mid-sagittal axis of the foot

The study contained a number of assumptions. The first assumption is that abnormal pronation of the foot is implicated as a cause of HV. Additionally, the study assumed an absence of gender differences for AOG. Finally, the satisfaction of inclusion criteria was based on the absence of soft tissue or osseous torsional changes as determined by clinical biomechanical assessment and gait analysis, under the assumption that range of motion at the hip, knee and ankle joints were equal between genders.

1.3 Definition of terms

‘Angle of gait’ (AOG) refers to the mid-sagittal axis of each foot in midstance relative to the direction of travel during gait, or clinically, the amount of in-toeing or out-toeing of the foot relative to the line of progression in the transverse plane.[8-11]

‘Body mass index’ (BMI) refers to the body weight (kg) divided by the square of the barefoot height (m).[12]

‘Calcaneal inclination angle’ (CIA) is a radiographically-based sagittal plane angle formed by the weight bearing axis, represented by the contact points of the calcaneus and first metatarsal head on the x-ray cassette, and a line drawn from this axis through the antero-plantar margin of the calcaneal tuberosity to the plantar margin of the anterior portion of the calcaneus. This measurement is obtained on a weight bearing lateral (LAT) view of the foot.[5]

‘First intermetatarsal angle’ (FIMA) is the radiographic transverse plane angle between the longitudinal axis of the first and second metatarsals, obtained from a weight bearing dorso-plantar (DP) view of the foot.[1]

‘First metatarsal protrusion distance’ (FMPD) is the distance between the relative length of the first and second metatarsals obtained from a weight bearing DP radiographic view of the foot.[1]

‘Foot progression angle’ (FPA) is the angle between the mid-sagittal axis of the foot and the direction of travel in the transverse plane during data collection obtained from the EMED-SF® pressure platform.

‘Hallux’ refers to the big toe as a whole, incorporating the proximal and distal phalanges.[1]

‘Hallux abductus angle’ (HAA) is the radiographic transverse plane angle formed by the longitudinal axis of the proximal phalanx of the hallux and the longitudinal axis of the first metatarsal, measured from a weight bearing DP view of the foot.[1]

‘Hallux abductus interphalangeus’ (HAI) is the radiographic transverse plane angle formed by the longitudinal axis of the proximal phalanx of the hallux and the longitudinal axis of the distal phalanx of the hallux, measured from a weight bearing DP view of the foot.[1]

‘Hallux Limitus’ (HL) refers to a progressive osteoarthritic condition affecting the first MPJ characterised by a reduction or limitation of hallux dorsiflexion on the first metatarsal head.[13]

‘Hallux valgus’ (HV) is a deformity of the first MPJ characterised by lateral deviation and often, external rotation of the great toe, and medial displacement of the distal end of the first metatarsal.[14, 15]

‘Lateral intermetatarsal angle’ (LIMA) represents the sagittal plane angular relationship between the dorsal cortices of the first and second metatarsals. It is the angle formed by the intersection of these two lines obtained from a weight bearing LAT radiographic view of the foot.[16]

‘Lateral stressed dorsiflexion’ (LAT SD) is the sagittal plane angle formed between the first metatarsal and the proximal phalanx as a reflection of weight bearing or functional dorsiflexion of the first MPJ. This measurement is obtained from a weight bearing LAT SD view of the first MPJ.[5, 17, 18]

‘Metatarsus Primus Varus’ is the term given to an increased first intermetatarsal angle (FIMA).

‘Rearfoot to forefoot axis angle’ (RFA ANGLE) represents the amount of rearfoot to forefoot abduction. It is the angle between the intersection of the rearfoot axis and the forefoot axis obtained from a radiographic weight bearing COMP view of the foot.[3]

1.4 Research questions

Results of the two pilot studies[6, 7] (Appendices 1 & 2) enabled the following research questions to be investigated:

(i) Was AOG derived from powdered footprints reliable?

(ii) Could the AOG obtained from powdered footprints be compared to the FPA derived from the EMED-SF® pressure platform?

(iii) Were the seven specific radiographic weight bearing angular and linear measurements to be used reliable?

(iv) Did subjects with HV have a more abducted AOG when compared to the control group?

(v) Did subjects with HV have a longer, shorter or elevated first metatarsal when compared to the control group?

(vi) Did the amount of first MPJ dorsiflexion influence AOG in subjects with HV when compared to the control group?

(vii) Did AOG reflect the amount of rearfoot to forefoot abduction in a foot with HV compared to the control group?

(viii) Did AOG become more abducted as the arch of the foot became lower in subjects with HV compared to the control group?

(ix) Did AOG differ significantly between feet in subjects with unilateral HV?

1.5 Summary

The purpose of this thesis was to provide information on the subject of AOG as it relates to the deformity of HV, in the population studied. Research questions will be answered via a methodology involving angular and linear geometric calculations obtained from powdered footprints and weight bearing radiographs. Findings of this investigation will be presented and discussed in an attempt to link clinical meaning to the results obtained. Limitations of the present study together with recommendations for further investigation will also be presented.

CHAPTER TWO

REVIEW OF THE LITERATURE

2.0 Introduction

The following Chapter provides a synopsis of the literature relating to HV and subject areas pertinent to the present investigation. A background into the nature of the deformity of HV is presented, with description of incidence, diagnosis, and aetiological factors. Emphasis is given to aetiologies of HV as they relate to biomechanical and radiographic findings of the deformity.

Secondly, a definition of AOG, along with literature findings of values considered normal, are presented. Despite variability associated with normal values of AOG, there appeared to be consensus regarding the large number of extrinsic factors capable of affecting AOG.

Finally, a background into the two uncommon radiographic views used as part of the overall radiographic analysis intrinsic to the foot, are explained. These were the LAT SD view used to measure first MPJ dorsiflexion and the COMP view used to assess the rearfoot to forefoot position.

2.1 Hallux valgus

The deformity of HV is characterised by lateral deviation and often, external rotation of the great toe and medial displacement of the distal end of the first metatarsal[14, 15] (Figure 2.1). In 1979 Burns[19] described the entity as '*merely a symptom of other causes*'. Shereff[20] defined the deformity as a '*lateral deviation of the great toe at the metatarsophalangeal joint*' which may be

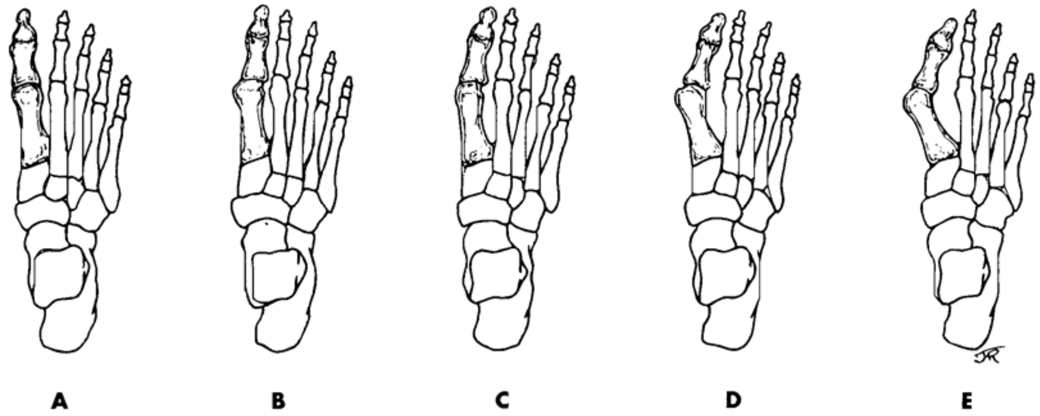

Figure 2.1: Stages of HV development ranging from the normal foot (A), progression of hallux abduction (B-D), through to dislocation of the first MPJ and loss of joint congruence (E) (adapted from Root, Orien & Weed, 1977)[21]

associated with other foot deformities. Hallux valgus cannot be described as a planar deformity as there are three-dimensional changes that occur with varying degrees of axial and coronal plane rotation of the first MPJ.[22] The severity of the condition is frequently dependent on the type of deformity, and the occurrence of HV can broadly be categorised into juvenile or adult forms.

2.1.1 Incidence

Hallux valgus has been described as one of the most common structural deformities observed in the lower limb,[1] although recent epidemiological analysis has not been undertaken. The true prevalence of HV is unknown,[14] however, a strong female tendency has been reported, with a female-to-male ratio of between 8:1 and 9:1 respectively.[14, 23-26] Literature reviews have cited incidences ranging from almost non-existent in some groups,[27, 28] to almost fifty percent in other groups.[29]

2.1.2 Aetiology

Little is known about the natural history of HV, when it first occurs, the rate of progression, and definitive aetiological factors.[14] Palladino[30] discussed the controversy surrounding the exact aetiology of HV since many factors have been implicated as a cause of HV, with the most likely scenario involving a combination of these factors (see Table 2.1).

2.1.3 Biomechanical assessment of hallux valgus

Review of the literature supported the general understanding that the aetiology of HV was commonly related to abnormal function of the foot. Reference to biomechanical causes of HV was made as early as 1938.[31] Abnormal pronation of the foot has been suggested as a cause of this deformity.[21, 25, 32-36] As a triplane motion, pronation of the foot involves abduction, dorsiflexion and eversion, a complex motion that may result in an abducted AOG during the stance phase of gait. Similarly, the reverse is also plausible, an abducted AOG as a primary positional structural deformity may cause pronation of the foot.[3]

A study conducted by Andrews et al[37] showed a relationship between abduction of the foot and a lower ankle inversion moment (r^2= 0.46). These authors suggested loading of the medial compartment of the knee could be decreased by increasing the amount of adduction of the great toe. This could occur through supination of the foot. Additionally, abduction or adduction of the forefoot on the rearfoot appeared to be specific to foot type, with differences between rigid and flexible foot types.

Table 2.1: Reported aetiologies of Hallux Valgus

Author	**Year**	**Primary Aetiology**
Hardy & Clapham[38]	1951	Increased first intermetatarsal angle
Villadot [39]	1973	Short first metatarsal
Root, Orien & Weed[21]	1977	Excessive pronation Ankle equinus Arthritic conditions Neuromuscular conditions Traumatic compromise
McNerney & Johnson[40]	1979	Generalised ligamentous laxity
Mann & Coughlin[15]	1981	Ankle equinus
Caputo & Walter[41]	1983	Genetic disorders or syndromes (Down syndrome, Ehler-Danlos syndrome, Marfan's syndrome)
Ross[36]	1986	Excessive pronation
Lamur et al.[42]	1996	Genetics Footwear Widened forefoot
Roukis, Scherer & Anderson[43]	1996	Decreased first MPJ dorsiflexion
Kura et al.[32]	1998	Footwear (heel height) Bony geometry Tendon imbalance Excessive pronation
Harris & Beeson[44, 45]	1998	Generalised hypermobility
Stevenson[25]	1990	Excessive pronation
Faber et al.[33]	1999	Excessive pronation Increased first intermetatarsal angle
Bryant, Tinley & Singer[46]	2000	Increased first intermetatarsal angle Long first metatarsal
Tanaka et al.[47]	2000	Hypermobility of first ray
Glasoe, Allen & Saltzman[34]	2001	Excessive pronation
Garrow et al.[14]	2001	Increased first intermetatarsal angle
Neylon, Johnson & Laroche[48]	2001	Long or short first metatarsal Increased proximal articular set angle (PASA)
Ferrari & Malone-Lee[49]	2002	Muscle imbalance (hallux abductor and adductor)
Ìncel et al.[50]	2003	Metatarsus adductus Elevated first metatarsal
Ferrari & Malone-Lee[35]	2003	Hereditary predisposition
Kernozek, Elfessi & Sterriker[24]	2003	Excessive pronation Footwear (high heels, narrow toe boxes) Abnormal subtalar and midtarsal joint pronation

MPJ: metatarsophalangeal joint

The literature suggests that biomechanical abnormalities, specifically, excessive pronation, is an important aetiological factor in the development of HV. Hence, the measurement of parameters relating to foot type[51] and the relative amount of foot abduction become important. Radiographically, this information can be assessed by examination of CIA and RFA angle.

Calcaneal inclination angle is measured from a lateral weight bearing view of the foot and has been thought to be an assessment of relative arch height.[5, 52] The higher the CIA, the higher the arch of the foot, and the less pronation occurring at the subtalar joint.[53] Conversely, the lower the CIA, the greater amount of pronation at the subtalar joint and the lower the arch of the foot.[53] According to Weissman[53] and Vito and Kalish,[52] measurement of CIA can therefore provide an indicator of foot type (low arch or high arch) and be used as a measure of pronation. This is of benefit in light of the problems associated with reliability of clinical rearfoot measurement.[54] However, Wearing et al[55] suggested changes in inclination angle of the calcaneus may not necessarily reflect rearfoot motion. In a critical review of hindfoot measurement, Menz[54] highlighted the subjectiveness of biomechanical assessment and questioned whether subtalar joint neutral is of any significant application clinically.

The RFA angle is obtained from a weight bearing COMP view of the foot, and provides an indication of the amount that the forefoot is abducted on the rearfoot. Measurement of the RFA angle is a potentially useful indicator of foot function. In an in-vitro study using cadaveric specimens, used to investigate the relationship of forefoot abduction to foot length, Lee et al.,[56] reported that loading of normal feet produced forefoot abduction in response to foot dorsiflexion and internal tibial rotation, although complete statistical data was not provided. However, ‘extreme’ foot types produced forefoot adduction in three out of four cases studied, but internal tibial rotation resulted in forefoot abduction in all four cases. It is therefore possible that similar discrepancies from normal may also occur in the presence of pathology or foot deformity, such as in HV. However there were serious limitations identified in the study by Lee et al.,[56] related to sample size, absence of anatomical structures capable of influencing foot motion, such as the function of the Achilles tendon, statistical methods and poor definition of foot types. ‘Extreme’ foot types were considered either rigid or flexible, however no indication was given as to the amount of rigidity or flexibility that was considered extreme. The restricted nature of the study highlighted the need for research to measure rearfoot to forefoot abduction or adduction in relation to AOG.

2.1.4 Radiological assessment of hallux valgus

The diagnosis of HV is achieved by the assessment of clinical signs and symptoms, and confirmed by radiographic examination. Specific radiographic findings are used to assess and monitor the progression of HV or the results of clinical or surgical intervention.

Perhaps the most important radiographic measurement relating to degree of HV deformity is the hallux abductus angle (HAA), measured on a weight bearing DP view (Figure 2.2). Abduction of the hallux is the most clinically obvious sign of HV. Normal radiographic parameters for HAA were investigated by authors as early as the 1950s. Since then most radiographic studies of HV have adopted the parameters used by these early authors as representative of normal. Specialised radiographic textbooks of the foot report normal values based on the findings of investigations prior to the mid 1970’s. Weissman’s[53] textbook on foot radiology, and some well referenced textbooks on foot surgery[1]

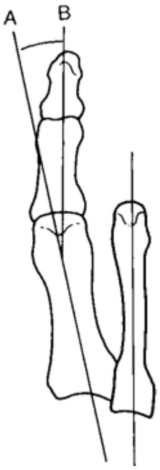

Figure 2.2: The HAA obtained from the intersection of lines bisecting the first metatarsal (A) and the hallux (B) (adapted from Schuberth, 1992)[57]

are examples of literature that have adopted the findings of early investigations suggesting normal HAA was less than 15°.[5, 21, 58, 59]

Review of the literature revealed some differences regarding normal values for HAA. Most authors agreed a HAA value of less than 15° was considered normal,[5, 23, 60, 61] however Hardy and Clapham[38] reported a range of 0°-20° as normal. This was supported by Antrobus[62] and, Houghton and Dickson[63] who found an average of 18.7° and 16.7° for HAA in their normal subjects respectively. Other authors attempted to grade the HV deformity according to degree of HAA. Kelikian[64] suggested 20° was a mild deformity, whereas Gentili[65] classified a mild deformity as having a HAA of 16°-25°. Palladino[30] identified the lower limit of HAA in normal subjects was 15° and the upper limit of normal as 20°. Steel et al[66] also stated normal HAA was less than 20°, with a range for normal being reported as 0°-32°. However, further inspection of their methodology raised some questions regarding the selection criteria for those subjects in their normal group. Kernozek et al[24] examined clinical factors for HV in normal subjects but used visual screening rather than radiographic assessment to determine HAA in their normal subjects.

Despite the reported good reliability of measurement of HAA and other radiographic variables,[7, 67] the literature has shown a considerable amount of variation when identifying normal parameters for HAA. For the purpose of this investigation a HAA value less than 20° was considered normal.[30, 38, 66]

Although HAA is not specifically thought of as an aetiological factor in the development of HV, it's progression becomes causative by way of functional disability of the first MPJ. That is, an increase in the HAA results in deviation of the normal relationship between the proximal phalanx of the hallux and the first metatarsal head, thereby decreasing the efficacy of the hallux in leverage, creating abnormal stresses on the first MPJ. This may lead to the development of degenerative joint changes, such as osteoarthritis and hallux limitus (HL),[68-70] ultimately resulting in ineffective or decreased dorsiflexion at the first MPJ. Radiographically, first MPJ dorsiflexion can be measured using a LAT SD view of the first MPJ. A normal range of first MPJ dorsiflexion has been suggested as being more than 65° in the sagittal plane.[71]

The degree of hallux abduction may influence the amount of foot abduction during gait. The question of whether abduction of the foot, and indirectly pronation, is a causative factor for HV, or a compensatory mechanism arises. This dilemma highlights the importance of research to measure the AOG in subjects with HV and those without the deformity.

The HV deformity is usually associated with an increased first intermetatarsal angle (FIMA),[34, 48] measured on a weight bearing DP view. The literature is inconclusive regarding the relationship between FIMA, also known as metatarsus primus varus, and HV. Most literature supports the relationship between metatarsus primus varus and HV[38, 46, 47, 60, 62, 72, 73] however Houghton and Dickson[63] found no relationship between metatarsus primus varus and HV in their study.

Landers[1] explained that a pathological imbalance occurs in HV as a result of basic stresses on foot structure. This results in hypermobility of the foot during gait, which allows for force to influence the alignment of the first ray. The FIMA has a direct relationship to the amount of abduction developing at the hallux, and has been considered a major factor in the development of HV.[47] A study comparing radiographic measurements between HV, HL and normal feet reported an increase in FIMA was significantly related to HV compared to the two other groups ($P< 0.05$).[46] Variability was reported in the literature regarding normal values for FIMA. One author considered FIMA less than or equal to 9° was normal,[74] whilst another stated the range of 8°-12° was normal[75]. Different ranges for normal values of FIMA were first suggested in 1974 by LaPorta,[59] who proposed that consideration should be given to the type of foot, whether rectus or adductus. A rectus foot was defined as *‘a foot type in which the angle of forefoot adductus is 22 degrees or less’*, and an adductus foot type was *‘a foot type in which the angle of forefoot adductus is 22 degrees or greater’*. Palladino[30] highlighted the normal range for FIMA in rectus feet as being 8°-12°, and 8°-10° in adductus feet.

Length and elevation of the first metatarsal in relation to the second metatarsal have been suggested as being predictive of first MPJ pathology.[16, 46, 76-78] However, the role of a long or short first metatarsal as a predisposing factor for HV remains controversial.[46, 48, 79] LaPorta[59] suggested normal weight bearing length of the first metatarsal when compared to the second was ± 2mm. In a radiographic study of normal, HV and HL feet, metatarsal protrusion distance was significantly greater in HV feet.[46] Hardy & Clapham,[38] and Duke et al.[79] supported this finding, however, Saragas & Becker[72] and Villadot[39] found no relationship between the length of the first metatarsal and the presence of HV. Furthermore, Duke and et al also noted that a HAA value greater than 20° was usually associated with a long first metatarsal[79], as were feet with a superimposed hallux abductus interphalangeus (HAI) deformity.[80]

Relative length of the first metatarsal may be assessed by measurement of the FMPD, on a weight bearing DP view. Radiographic measurement of metatarsal protrusion distance has been described in the literature.[59, 81] Elevation of the first metatarsal can be assessed by measurement of the intermetatarsal angle between the first and second metatarsals (LIMA) on a weight bearing LAT view of the foot.[16] Both of these parameters provide information relating to geometry of the first metatarsal.

2.2 Angle of gait

Although there is considerable literature relating to abnormal mechanics as a risk factor for foot deformities, such as HV, to the author's knowledge, the relationship between AOG and HV has not been reported in the literature.

The AOG refers to the mid-sagittal axis of each foot in midstance relative to the direction of travel during gait, or clinically, the amount of in-toeing or out-toeing of the foot relative to the line of progression[8-11] (Figure 2.3). Angle of gait has been implicated as an important factor in biomechanical pathologies, for example, as a predictor of knee injury in healthy individuals.[37] According to Ho et al,[82] gait disorders secondary to out-toeing and in-toeing are the most common reason for referrals of pre-school children for gait assessment.

2.2.1 Normal reference ranges for angle of gait

Angle of gait has received little attention in the literature, and studies of this parameter have revealed a large range of values, between 5° to 13°,[9, 71, 83-86] of abduction from the direction of travel. Furthermore, AOG may also be influenced by walking speed with the amount of abduction being possibly related to leg dominance during gait.[87] Additionally, tactile feedback derived from the walking surface and amount of friction on the walkway have been thought to be important.[8, 87] Holden et al,[8] proposed that variability in the AOG must be due to structural and morphological factors. Furthermore, variability in measurement methods may have accounted for differences among observers regarding normal values for AOG.

2.2.2 Factors affecting angle of gait

Factors that have been proposed to influence AOG include soft tissue and osseous torsional or positional changes in the hip, femur and tibia, amount of malleolar torsion, and adduction or abduction of the foot.[86] For example, excessive internal torsion of any component of the leg may cause an adducted

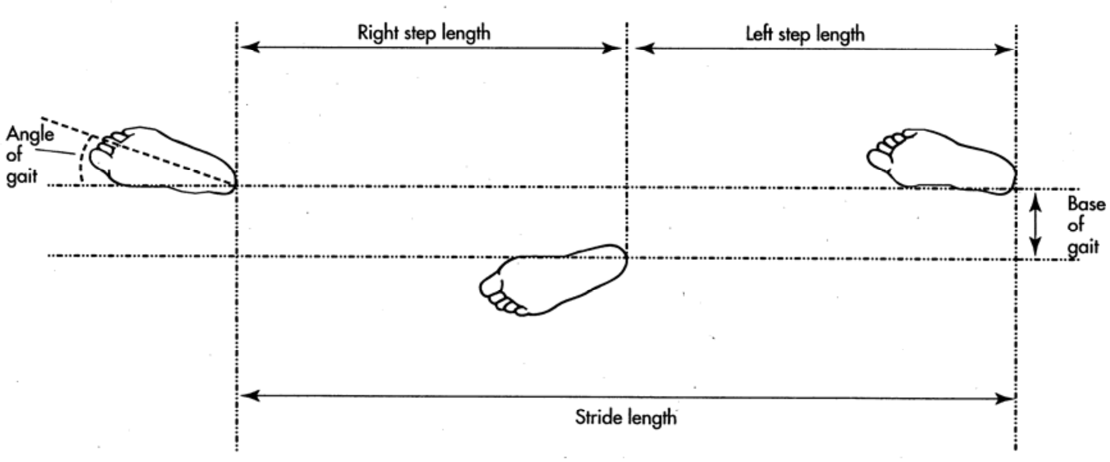

Figure 2.3: Angle of gait in relation to stride length, step length and base of gait (adapted from Wernick & Volpe, 1996)[85]

AOG and a squinting patellae, whereas excessive external rotation may cause an abducted AOG.

2.2.3 Dynamic angle of gait

Sutherland et al[88] described the changes which occur in AOG during the typical gait cycle. The first part of the gait cycle revealed a constant amount of abduction. During the second period of double support (between the event of opposite foot strike and toe-off), there is an adduction of the foot clearance during the early portion of the swing phase. Starting at toe-off, the foot abducts as it simultaneously dorsiflexes to clear the foot during swing phase. In summary, the AOG remains abducted until heel rise, followed by a small amount of adduction during second period of double support. During the swing phase, the foot is in an abducted position in initial swing phase, followed by foot adduction during the late portion of the swing phase[88] (Figure 2.4).

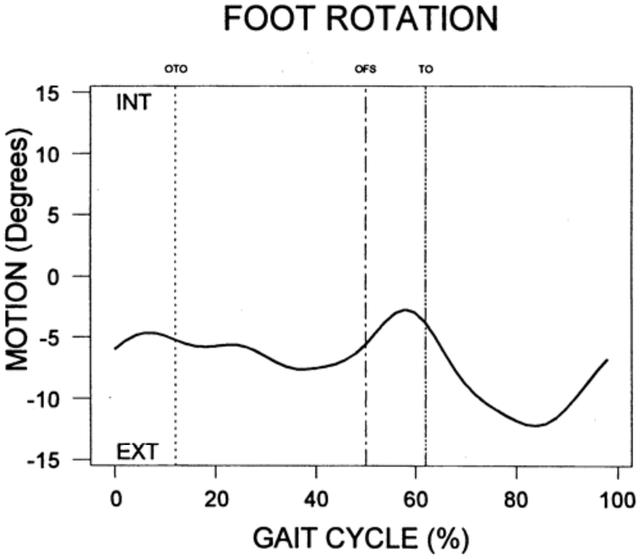

Figure 2.4: Amounts of internal (adduction) and external (abduction) rotation of the foot during normal gait (adapted from Sutherland et al, 1994)[88]

2.2.4 Static versus dynamic footprint data

Kippen[89] showed a significant relationship between dynamic and static footprint data. However Wilkinson & Menz[90] identified limitations in the study by Kippen,[89] relating to identification of a reproducible reference point on the curvature of the heel, and the use of this particular technique to barefoot individuals. Another criticism was in the design of this reliability study which involved the use of only a single subject. This may have indicated that the examiners may have remembered values obtained between tests.

Given that foot placement can influence stabilising reactions, McIlroy & Maki[91] studied the preferred foot placement during stance, in an attempt to standardise a position for balance testing. Subjects were asked to stand with their feet positioned comfortably. These authors found only a weak correlation between the width of stance (base of gait) and static AOG (R: -0.22, P= 0.002). There was large between subject variability in both young and elderly subjects, with a range of –13° to 52°, (a negative value implied in-toeing). The large amount of variation in this angle may be partly due to subject selection and measurement error of this methodology, which involved a tracing outline of the foot and drawing angles.

2.2.5 Angle of gait and foot compensation

Whittle[92] highlighted the potential compensations that can occur as a result of an abnormal AOG. During normal walking, the foot is placed in a few degrees of abduction on the ground approximately in line with the direction of progression. Aside from torsional or positional parameters in anatomical segments proximal to the foot, abnormal or pathological degrees of an abducted or adducted AOG may occur as result of deformity within the foot. Consequently, an abnormal AOG may lead to an abnormal position of ground reaction force relative to the leg. In the case of a more adducted AOG, the ground reaction force is more medial than normal, causing external adductor moments at the more proximal joints.[92] Another important factor relates to a functional shortening of foot length. That is, in either an adducted or abducted foot position, the relative length of the foot is reduced in the line of progression, causing ground reaction force during late stance phase and pre-swing phase to be more posterior than normal. In turn, the leverage for the ankle plantarflexors to create an internal plantarflexion moment is reduced.[92]

2.2.6 Methods of measuring angle of gait

2.2.6.1 Traditional methods

There have been numerous studies examining the measurement of gait parameters. One particular study measured step length and step width using video and a grid system incorporated on a walkway and concluded that valid and reliable measurements could be obtained.[93] A variety of techniques for measuring AOG have been used, including plaster of Paris, adhesive corn plasters, talcum powder, gauze injected with ink, moleskin, force platforms, absorbent paper, glass plates, video and motion analysis systems.[10, 82, 87, 90, 93-101] Various methodologies to measure AOG are summarised in Table 2.

Until the study by Holden et al,[8] most evaluations of AOG involved measurement relative to a line drawn through the middle of a walkway. Other studies have calculated the line of progression by using only ipsilateral footprints.[98] Wilkinson et al[11] argued this did not account for the variability in the line of progression caused by the contralateral foot. These authors believed the line of progression was not simply a longitudinal bisection of the platform, and instead used a line of progression which gave consideration to both feet. Validity of the line of progression has also been questioned by other authors.[11, 97]

The ‘footprint method’ of assessing gait parameters has been shown to be easy, reliable, valid, inexpensive and clinically adaptable.[3, 87, 97, 99, 102] A recent study investigating the variability in outlines of barefoot inked footprints for forensic purposes showed a large variability between subjects but a high degree of reliability for multiple measures from the same subject.[103] However,

Table 2.2: Reported methodologies used to measure AOG

Author	Year	Methodology
Fukushima[94]	1955	Powdered plaster of Paris
Ogg[95]	1963	Paper Corn pads Felt tip markers
Scrutton & Robson[10]	1968	Talcum powder Linoleum
Burnett & Johnston[96]	1971	Gauze injected with ink
Boenig[97]	1977	Moleskin Ink Paper
Levangie et al[99]	1983	Moleskin Water based ink Paper
Katoh et al.[100]	1983	Force plate Stainless steel tape mats
Clarkson[87]	1983	Moistened absorbent paper
Rutherford [101]	1983	Glass plates Mirrors
Bertoti[98]	1986	Moleskin impregnated with water based ink Paper
Wilkinson & Menz[90]	1997	Transparent grid Laundry markers Metal rulers Alcohol swabs White cardboard Coloured talcum powder Artists' fixative Lamination
Ho et al.[82]	2000	Motion analysis system

variability was examined between subjects regarding foot dimensions and concluded that inked footprints are highly individual. In addition to those limitations relating to the footprint method already presented, it's simplicity did not account for record of walking, or movements of the trunk and arms.[10]

2.2.6.2 Electronic methods: EMED–SF®

Few studies have investigated the simultaneous collection of footprint data, and to the author's knowledge, none have investigated the simultaneous comparison of powdered footprints and EMED-SF® data. Urry and Wearing[104] compared ink footprints to electronic footprints from a Musgrave force platform as a means to evaluate differences in geometric parameters. Intra-rater reliability of geometric analysis of electronic footprints have been reported to be high.[105] Reported potential problems associated with electronic footprints are poorly delineated and irregular borders[106] and inadequate contact area as a result of sensor resolution.[104]

The EMED-SF® pressure platform analysis system is an instrument used for recording and evaluating static and dynamic pressure distribution on flat surfaces. Numerous parameters of foot function can be investigated using this system.[107] The EMED-SF® platform produces a maximum pressure profile, which depicts the contact area and pressure distribution of the foot. Angle of gait can be calculated from this pressure distribution picture, using the EMED-SF® Geometry program. The Geometry program refers to the AOG as the foot progression angle or FPA, defined as the angle between the mid-axis of the foot and the direction of travel during data collection. As a result, this angle can be used to describe the angle at which the foot contacts the ground.

2.3 Radiographic evaluation

The use of radiographic images to investigate foot disorders is common practice in orthopaedics. Whether used for assessment, diagnostic or comparative purposes, radiographs provide information, which may influence clinical decision-making. Frequently angular and linear measurements are undertaken in an attempt to quantify the nature of a deformity,[81, 108] and may be used for pre-operative planning of procedures. Subsequent films are also used for comparative purposes and to assess the results of intervention.

2.3.1 Sources of error

Sources of error relating to radiographic assessment include the choice of landmarks, construction of lines,[109] reading of the measurement tool, over-exposure of the x-ray,[110] foot position, relationship of the foot to the central ray and the cassette,[84, 111] and arch height in relation to declination of the metatarsals.[112] Additionally, magnification and distortion of foot bones has also been recognised.[113, 114]

2.3.2 Weight bearing versus non-weight bearing

Previous literature has identified controversy regarding whether weight bearing radiographs were more indicative of clinical findings than non-weight bearing radiographs. A standard weight bearing lateral view taken in the normal angle and base of gait was reported to be similar to findings during gait.[115, 116] However it has been demonstrated that no significant differences have been shown between angular measurements taken from radiographs when the person stands in their typical angle and base of gait, and those taken of the same subject standing with their feet together.[84] In contrast, angle and base of gait have been reported to be of critical importance when comparing the sagittal plane relationship between the first and second metatarsals.[116] Finally, discrepancies between normal reference ranges for angular measurements have been reported,[66] together with a divergence of opinion regarding angular relationships that may be indicative of pathology. For example, metatarsus adductus has been implicated as a cause of HV,[61] and length of the first metatarsal may be predictive of first MPJ pathology.[16, 46, 76-78]

2.3.3 Repeatability

Repeatability of radiographic measurements of the foot has been investigated by many authors with mixed results. Some studies have shown large variation among raters, suggesting pre- and post-operative angles should not be compared unless measurements have been undertaken by one rater.[117] As an example, the variation between raters for radiographic measurement of the first intermetatarsal angle was 0.67 - 4.0 degrees, and for the hallux valgus angle was 1.52 – 7.7 degrees. Use of radiographic parameters when discussing HV becomes imperative. High intra and inter-rater reliability have previously been demonstrated when measuring angular measurements in HV deformities.[67] Specifically, intra and inter-rater measurements of the FIMA and HAA produced a range of 5 degrees or less.[67] In addition to being highly reliable, the importance of using weight bearing x-rays to provide an accurate representation of foot structure has been mentioned in the literature.[118] It has been thought intra-rater reliability improves with experience,[119] although some studies reported no improvement in reliability with increasing experience.[67, 74, 120] Coughlin and Freund[67] reported no statistical difference between intra and inter-rater reliability of physicians with or without training respectively (P= 0.47, P= 0.15). Condon et al[74] reported similar findings with a reliability of 0.88 for the observer with least experience, and a reliability of 0.85 for the most experienced observer.

Although, the most commonly used podiatric radiographic variables (HAA, FIMA, FMPD, CIA, LIMA) have traditionally been used with established reliability and validity, those used to assess dorsiflexion of the first MPJ (LAT

SD) and rearfoot to forefoot position (RFA angle) have not been thoroughly investigated.

2.3.3.1 First metatarsophalangeal joint dorsiflexion

Measurement of first MPJ range of motion has involved static and dynamic methodologies ranging from use of an electromechanical oscillator on cadaver specimens,[121] weight bearing radiographs,[17, 18, 64] goniometry,[58, 71, 86, 122-131] digitisation using video data,[71, 132] and, use of an electromagnetic tracking device.[69] However detailed methodology in measuring first MPJ range of motion in the literature has been shown to be somewhat limited with regards to a standardised technique to quantify and reliably reproduce values given for normal range of motion.[17, 122] Variability in such methodologies highlights the need for a consistent method utilising reproducible landmarks and points of reference to measure first MPJ range of motion. This is of particular importance when rating scales of radiographic deformities are consulted to assess foot function, operative interventions and clinical outcomes.

Reliability of the LAT SD view of the first MPJ methodology has received little attention in the literature. Joesph[18] was the first author to report on significance of radiographic measurement of first MPJ dorsiflexion using a weight bearing lateral radiograph. A limitation of his study was the exclusion of women, a group largely afflicted with deformities affecting the first MPJ. Some years after the study by Joesph,[18] a further investigation by Buell et al[17] was undertaken to establish normal values and test the methodology for obtaining first MPJ range of motion. These authors compared clinical measurement of first MPJ range of motion to that found radiographically, and reported a high ‘correlation’ for active and passive dorsiflexion. Clinical unassisted dorsiflexion averaged 90° and the radiographic values averaged 89°; clinical assisted dorsiflexion was 105° and the radiographic value averaged 100°.[17] Limitations of the study by Buell et al[17] were they failed to include subject demographics, incomplete details of the methodology and instrumentation used, and inadequate statistical analysis was performed. Their results were reported as average values only. There was a mention of further data evaluation, however this was not explained or presented, and there did not appear to be any use of further statistical analyses.

Measurement of first MPJ dorsiflexion from the LAT SD view allows an objective and functional weight bearing depiction of sagittal plane first MPJ dorsiflexion. This would be of clinical significance when evaluating first MPJ pathology and treatment outcomes. The measurement technique enables quantification of first MPJ dorsiflexion, eliminating a common potential source of error such as movement of markings drawn on the skin.

2.3.3.2 Rearfoot to forefoot position

Reliability of the COMP view[4] in measuring the RFA angle has not been established. Although the composite view has not been used extensively in research or clinical practice, it presents the advantage of viewing the entire skeletal anatomy of the foot. Radiographic determination of the RFA angle was first described and used in a study in which the radiographic axis was transferred onto footprints generated from a force platform, reducing potential sources of error such as location of anatomical landmarks and soft tissue influence.[3] Mean values of 8.4° and 0.7° were reported for the RFA angle from static and dynamic situations respectively.[3] However, reliability parameters for the RFA angle were not established by Freychat et al[3], and to the author's knowledge, there have not since been any investigations to do so. Additionally, the lack of comparative studies and establishment of normal values identified a void in the existing literature.

Relevance of the RFA angle stems from the proposal that the forefoot and rearfoot may act independently, and foot position is influenced by mobility around the midtarsal joint.[133] In this way, the RFA angle, may allow static measurements to reflect dynamic function, such as pronation and supination of the foot.[134] Additionally, it provides a transverse plane measurement of the forefoot to rearfoot relationship. Historically clinical examination has suggested a relationship between metatarsus adductus and HV. Some authors supported this relationship[21, 61, 135] and others did not.[46, 136]

It has been proposed that pronation and supination can be influenced by movement of the forefoot on the rearfoot[137] and that planal dominance of an individual foot can determine the primary plane of compensation.[138] The concept of planal dominance was illustrated by Green and Carol,[138] suggesting the location of the subtalar and midtarsal joint axes was important in determining the amount of compensation occurring in a particular plane. For example, if the subtalar joint axis falls parallel to the transverse plane, this will allow primarily transverse plane motion (abduction - adduction) and very little frontal plane motion (inversion – eversion). The more vertical the subtalar joint axis for an individual, the greater the amount of transverse plane motion; the more horizontal the axis, the greater the amount of frontal plane motion.[138] Foot pathologies such as adult acquired flatfoot and tibialis posterior tendon dysfunction, resulting in excessive pronation depict a possible mechanism of compensatory forefoot abduction.[139-141] In addition to acting as a plantarflexor and invertor, the tibialis posterior muscle itself also functions as an adductor of the forefoot at the midtarsal joint, opposing the action of peroneus brevis.[142] Additionally, forefoot abduction has clinical relevance regarding tightness of the plantar aponeurosis, indicating a more abducted or open foot type.[143] Subsequently, measurement of the RFA angle, using the COMP view, may be indicated in future research related to transverse plane pathomechanics.

2.4 Summary

The literature reviewed in this thesis has supported mechanical aetiologies in the development of HV, characterised by abnormal subtalar and midtarsal joint pronation, leading to first ray hypermobility and stress resulting in a deformity of the first MPJ.[24, 34, 144, 145] The association between abnormal foot function and the development of HV is controversial because of the lack of valid measurement techniques to quantify biomechanical parameters of the foot. Despite hypermobility being strongly implicated in the aetiology of HV, hypermobility is difficult to quantify.[146] It has been suggested abductory forces lead to greater deformity in HV.[35] It has been noted in some clinical observations that patients demonstrate arch collapse without excessive heel valgus or excessive abduction of the forefoot.[48]

In the absence of an established valid and reliable method for quantifying subtalar and midtarsal joint motion, any aetiology related to abnormal biomechanics is subjective in nature. In order to consider all components contributing to foot function, it seems prudent to consider alternative foot measurement techniques that have high levels of reliability and validity.

Clinical observation suggests an association between HV and an abducted AOG. Given the established relationship between excessive pronation and foot abduction, assessment of transverse plane motion, specifically AOG, may be important in providing further insight and understanding of the complex nature of the aetiology of HV. Gait analysis using footprint impressions is a simple and inexpensive method of obtaining valuable information relating to foot dynamics.

Radiographic measurement of foot parameters provide an objective assessment of foot structure and function in HV, reducing sources of error and subjectivity associated with clinical observation. Of the radiographic parameters reviewed, two groups of variables important for assessment of HV have emerged. The first group comprised those variables related to the aetiology or important in monitoring the progression of the HV deformity. Specifically, these were HAA, FIMA, FMPD, and LIMA. The second group consisted of those factors capable of influencing AOG, specifically RFA angle and first MPJ dorsiflexion measured by LAT SD. The variable CIA was considered important in both groups, given its aetiological implication as a predictor of foot type, as well as its capability of influencing AOG and the subsequent amount of pronation or supination occurring during gait.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

The aim of this study was to investigate AOG and radiographic characteristics of subjects with and without HV. This Chapter provides a detailed description of the methodology, including the aims of pilot studies in the early stages of the investigation. A summary of the study design, subject demographics and recruitment is provided. This is followed by description of data collection procedures, the criteria used for inclusion and exclusion of subjects, and ethical considerations. Special focus is given to the exact methodology of calculation of AOG and the measurement of radiographic variables, with the use of diagrams for clarification.

3.1 Pilot studies

Pilot studies were undertaken in order to provide reliability and validity parameters for the variables to be measured, and to establish intra-rater reliability.

The first pilot study (Appendix 1) consolidated quantification of AOG from powdered footprints as a reliable and valid method, reporting intra-rater Pearson's product moment correlations of 0.94 and 0.93 for two observers, with no significant difference between them (t = -1.63, P = 0.108), indicating the methodology could be used in the present study.

The second pilot study (Appendix 2) enabled reliability parameters to be established for various radiographic angular and linear measurements that would be used in the present study, particularly for the two uncommon radiographic views, namely the LAT SD view and the COMP view. Results indicated all measurements could be used reliably, specifically, the LAT SD view of the first MPJ, was shown to be a reliable method of quantifying the amount of hallux dorsiflexion in the sagittal plane. Similar reliability was observed for the COMP view of the foot, providing a unique method of assessing the rearfoot to forefoot relationship in the transverse plane. Intra-rater reliability of radiographic measurements ranged between *R* = 0.65 - 1.00 for the LAT SD view, and between *R* = 0.91 and 0.99 for the COMP view. Inter-rater reliability of radiographic measurements ranged from *R* = 0.82 - 0.99. Specifically, LAT SD showed *R* = 0.87 with a mean difference of –1.47 (CI: -3.42, 0.47), indicating no significant difference (*t* = 1.54, *P* = 0.13). The RFA angle showed *R* = 0.92 with a mean difference of –0.15 (CI: -1.05, 0.74), indicating no significant difference (*t* = 0.35, *P* = 0.73).

3.2 Study design and subjects

A prospective observational quasi-experimental case-control study design was used. Participants in the study were grouped into two study groups, namely, those with HV and a control group. Demographic characteristics of the sample that were collected included age, weight, height and body mass index (BMI).

3.3 Recruitment

Convenience sampling was used to obtain all subjects involved in the study, and recruited from the author’s private practice podiatry clinic in the Perth metropolitan area. Subjects were screened by the researcher to satisfy the criteria for inclusion or exclusion. Subjects signed an information and consent form, enabling participation in the study (Appendix 3), and were coded alphanumerically into each group prior to data collection.

3.4 Data collection procedures

3.4.1 Inclusion criteria

Hallux valgus subjects fulfilled the following criteria:

- Read, understood, and completed the subject information and consent form for participation.
- Reached skeletal maturity and exhibited a measured HAA of greater than 20° on a weight bearing DP radiograph.[1]
- Had the specified set of radiographs taken by the radiographer allocated to the study. Radiographs were angle and base of gait weight bearing views, and included bilateral DP and LAT views of the foot, a COMP view of the foot, and a LAT SD view of the first MPJ.

Control subjects fulfilled the following criteria:

- Read, understood, and completed the subject information and consent form for participation.
- Reached skeletal maturity and exhibited a HAA of less than 20° on a weight bearing DP radiograph.[1]

3.4.2 Exclusion criteria

Hallux valgus and control subjects were excluded from the study if they had any of the following:

- A history of lower limb surgery
- A history of trauma to the lower limb

- A history of neurological disorders that directly affect gait
- Used walking aids
- Displayed gait abnormalities; soft tissue or osseous torsional or positional changes in the hip, femur and tibia; an excessive amount of malleolar torsion; an intrinsic adduction or abduction deformity of the foot; as detected by clinical biomechanical assessment
- A history of congenital hip dysplasia
- A history of systemic disease, e.g. sero-negative or sero-positive pathology
- A history of hypermobility syndromes such as Ehlers Danlos or Marfan's Syndrome

3.4.3 Ethical considerations

All subjects participating in the study were required to read, understand and sign a freedom of consent form prior to participation, approved by the Human Research Ethics Committee of the University of Western Australia (see Appendix 3). This document served to inform the subject of any associated risks of the research, indicating the research would be conducted in a manner acceptable to the National Health and Medical Research Committee (NHMRC).

Participants involved in the study were not subjected to invasive procedures. Confidentiality of subjects was achieved via alphanumerical coding, known only to the researcher and primary supervisor. All data and documentation were to be kept securely in the Centre for Musculoskeletal Studies, University of Western Australia, for a period of five years. The data were saved on a Microsoft Excel® spreadsheet on the hard drive of the researcher's home computer, with password security. All data were entered onto an individual participant data recording sheet with the appropriate alphanumeric code.

Radiographic examination of subjects with HV forms an integral component of the normal comprehensive assessment of the deformity, therefore, obtaining radiographs for this group did not represent an ethical issue. Safety parameters relating to x-ray exposure were followed. According to Bryant[147] and the National Health and Medical Research Council (2002: 23) "*radiation doses to subjects shall be kept to a minimum level practicable, and the accumulated effective dose equivalent to any individual subject in any year shall not exceed 5 millisievert*".

Based on the views needed for the study and the radiographic equipment used, a skin entrance dose per exposure of 160-212 microgray was anticipated. Each subject had no more than 5 views taken bilaterally with a total of 12 exposures, making the total skin entrance exposure dose per subject 1920-2544 microgray. This was equivalent to 1.92-2.54 millisievert of x-ray radiation, which was below the recommended yearly effective dose of 5 millisievert for volunteer studies. Additionally, radiographs of the feet are considered very safe due to the low radiation exposure and ability to protect all body organs from scatter radiation.[147] Radiographers used appropriate screening measures to protect each subject.

Radiographic views for the control subjects were taken for research purposes only. The Human Research Ethics Committee at the University of Western Australia approved the use of ionizing radiation for the purposes of obtaining foot radiographs of the feet of control subjects.

3.4.4 Data collection

All data were collected by the same researcher, and recorded in exactly the same manner for each subject. First point of communication was via consultation with the subject, presentation of the subject information and informed consent document. Opportunity was provided for discussion and answering of questions raised by the participant to ensure full comprehension of the document to be signed.

Once participation was confirmed, demographic information was collected. The subject was then examined to satisfy inclusion into one of the study groups. Only one subject was assessed at any one time. This reduced any possibility of data confusion and ensured quality control. The same researcher performed all handling of data. This included data recording, saving and computer spreadsheet input. Reduction of double handling of data reduced the possibility of data entry error. To account for any discrepancies in data entry, the researcher randomly crosschecked raw data and spreadsheet entries for any processing errors.

3.4.5 Procedures

3.4.5.1 Angle of gait

Footprint data were obtained using 10m lengths of white paper (80gsm) measuring 91.5cm in width. The test environment remained the same for all subjects. The paper was laid out over a linoleum covered concrete floor for the entire 10m length. A chair was positioned at either end of the paper with a plastic container measuring 33cm in length, 22cm in width and 13cm in depth containing commercially available talcum powder mixed with blue oxide

(Diggers® Oxide Colouring) to a mixture ratio of 1:100. The level of coloured talcum powder was maintained at approximately 4cm depth in the plastic container, which was placed at the base of the chair at one end.

Prior to data collection, the subject was allowed a period of familiarisation and instructed to walk up and down the walkway a few times. The subject was then instructed to place their feet in the container and gently shake off any excess powder. The container was removed and the subject was instructed to rise from the chair and walk at a comfortable self-selected cadence to the other end. The subject was told to commence with the right foot, look straight ahead, and on reaching the other end of the walkway sit down. Following this, artists' fixative (Micador® Fixative Workable Mat) was sprayed on each footprint, and the subject's alphanumeric identification code was recorded on the paper, which was then moved aside to air dry.

Four consecutive footprints were preserved by placing a piece of transparent self-adhesive contact plastic (3M® Contact) over the entire footprint, starting with either the second or third footprint. Variability in the chosen initial footprint for analysis was related to differences in subject's stride length, and to allow for effects of acceleration and deceleration during their walking trial. In each case, two consecutive left and two consecutive right footprints were collected from the middle section of the footprint sample and preserved for analysis. The 10m length of paper was rolled up and stored in a locked cupboard for the interim period prior to AOG measurements (undertaken at a later stage).

Measurement of AOG using powdered footprints for all subjects was conducted in the same environment. The individual 10m lengths of paper were examined on a flat table in a well-lit room. A fine (0.5mm) water soluble overhead projection marker (Artline® 803 Fine) was used for marking. A one-meter stainless steel ruler and smaller transparent plastic 30cm ruler (Linex®) were used to draw lines, and angles were measured using a transparent plastic 15cm protractor (Celco®) with increments of one degree, allowing recording of measurements to 0.05° resolution. Other items used included a calculator (Canon® F-800 Scientific Statistical Calculator), and a tabulated sheet for recording results (Appendix 4).

A transparent acetate grid measuring 21cm by 37.5cm, made up of parallel lines, was placed over the selected footprint. The vertical border of the grid was positioned parallel to the border of the paper closest to the medial side of the foot, aligning the top corner of the grid with the apex of the hallux and the medial side of the forefoot. To ensure the vertical border of the grid was parallel to the right or left border of the paper, the distance between the vertical border of the grid and the border of the paper was measured at top and bottom margins of the grid. At the level of the apex of the hallux, the angle of the line of the grid was transferred onto the paper and labeled line (A). The grid was then used to transfer a similar line on the paper across the posterior aspect of the heel, parallel to line (A). This line was called line (B). The vertical border of the grid adjacent to the medial side of the forefoot was marked at either end. The grid was removed and the two points joined to formulate the line of progression (Figure 3.1).

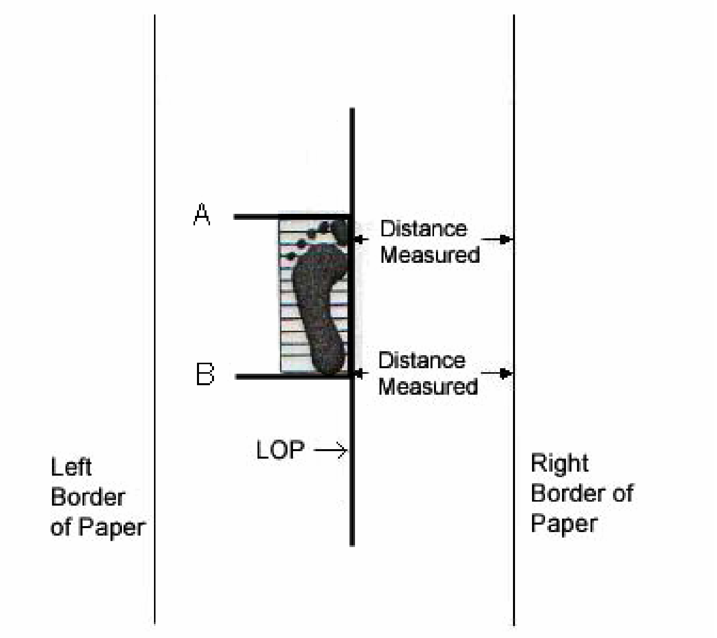

Figure 3.1: Placement of transparent grid to ensure parallel lines representing the apex of the hallux (A) and posterior border of the heel (B) and equal distances between the vertical border of the grid and the right edge of the paper, adapted from Taranto et al[6] (LOP = line of progression)

The footprint was then divided into thirds, and further division of the proximal third into half forming lines (C), (D) and (E) to provide an accurate reference point of medial and lateral foot margins. Line (C) became the forefoot reference and line (E) the rearfoot reference. The intersection of line (C) and (E) with the medial and lateral aspects of the footprint were identified, the length of the line was then measured and bisected, with the midpoints of these lines marked on the footprint. Line (F) was obtained by connecting the midpoints of lines (C) and (E). This line was extended beyond the proximal margin of the footprint (X) and became line (FX), which represented the axis of the foot (Figure 3.2). The line corresponding to the medial side of the forefoot originally marked on the paper

Figure 3.2: The length of the footprint was measured from (A) to (B) and divided into thirds (C) and (D), and the proximal third further divided into half (E). The width of the footprint was measured at 17% (E) and 66% (C) of the foot length and midpoints obtained giving the foot axis (FX) (adapted from Taranto et al)[6]

(line of progression) was extended to the point of intersection of line (FX). The angle formed was termed the AOG.

3.4.5.2 Radiographic views

Three radiographers from the same radiology clinic were used for the study. A period of training was undertaken with the researcher to inform the radiographers of the procedural protocol and specific views required. The same x-ray machine was used for all radiographs. Radiographic views were all weight bearing and included DP, LAT, LAT SD of the first MPJ and COMP views. A summary of focal film distance, position and angle of the central ray, and, exposure used is presented in Table 3.1. Standard weight bearing DP and LAT views were taken in the subject's normal angle and base of gait.

The LAT SD view[17, 18, 148] of the first MPJ was taken as per a standard lateral view, however the central ray was directed at the first MPJ. The knee was flexed 40° and the heel raised off the ground to the point where the first MPJ was in maximum dorsiflexion, without any obvious frontal or transverse plane movement.

For the COMP view,[4] a double exposure was required. The subject was positioned as per the DP view. The first exposure involved positioning of the patient in an upright posture, with the foot to be imaged extended forward and the plantar aspect of the foot in contact with the film (Figure 3.3a). The central ray was centered over the ankle and the first exposure taken (Figure 3.3b). The subject was then required to keep the foot to be imaged in the same position, but step forward with the opposite leg. The x-ray tube was not displaced and as a result the central ray passed through the posterior aspect of the ankle joint and the second exposure taken (Figure 3.3c). Both exposures were set at 62kV, 125mA and 0.05sec.

3.4.5.3 Radiographic angles

Radiographic measurements were conducted using a radiographic light box, in a darkened room. Acetate transparencies were placed over each radiograph and secured using clear adhesive tape, so there was no movement and it was not necessary to mark the actual radiograph. Using a fine (0.5mm) water soluble pen, angular and linear measurements were made on the radiographs

Table 3.1: Radiological parameters of angular and linear measurements

View	FFD	Position and Angle of Central Ray	Exposure
Dorsoplantar	90cm	20° from the vertical directed at base of third metatarsal	54kV, 100mA, 0.04 sec
Lateral	90cm	90° from the vertical directed at the cuboid	54kV, 100mA, 0.04 sec
Lateral Stress Dorsiflexion of first MPJ	90cm	90° from the vertical directed at the first MPJ	54kV, 100mA, 0.04 sec
Composite	90cm	Position 1: Central ray vertical over the ankle joint.	62kV, 125mA, 0.05 sec
	90cm	Position 2: X-ray tube not displaced, central ray through posterior aspect of ankle joint	62kV, 125mA, 0.05 sec

FFD : focal film distance

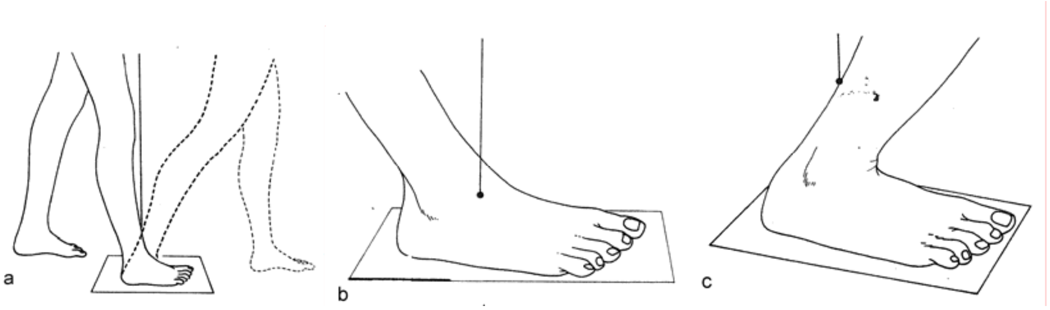

Figure 3.3: Radiographic technique for COMP view showing position of subject and central ray; (a):plantar aspect of the foot in contact with the ground; (b): central ray centered over the anterior aspect of ankle joint for first exposure; (c): central ray passes through posterior aspect of ankle joint for second exposure (adapted from Montagne et al, 1981)[4]

and recorded. After each measurement, the acetate sheets were removed, and wiped clean of any marks. Other items used included a transparent plastic protractor with increments of one degree, a transparent plastic ruler with increments of 1mm, a calculator, and a tabulated sheet for recording results (Appendix 5).

For each subject, seven measurements were obtained for the left and right feet (14 per subject). These included CIA, HAA, FIMA, FMPD, LAT SD of the first MPJ, RFA angle, and LIMA. Radiographic measurement of these variables have been shown to be reliable.[7, 67] The author's intra-rater reliability confirmed this finding, reporting correlation coefficients ranging from 0.93 to 0.95 for the seven dependent variables.[7]

Radiographic measurement of first MPJ dorsiflexion was obtained using the LAT SD view. The LAT SD[17, 18] view is a reflection of the weight bearing or functional dorsiflexion of the first MPJ. The dorsal and plantar cortices of the proximal and distal thirds of the first metatarsal shaft were identified, and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by the intersection of these two lines represented the amount of first MPJ dorsiflexion (Figure 3.4).

Radiographic measurement of the RFA angle was obtained using the COMP view. The RFA angle[3] represents the amount of intrinsic rearfoot to forefoot abduction. The posterior sclerotic margin of the calcaneus was bisected to obtain the point representing the posterior border of the calcaneus. The most medial and lateral margins of the calcaneocuboid joint were identified and

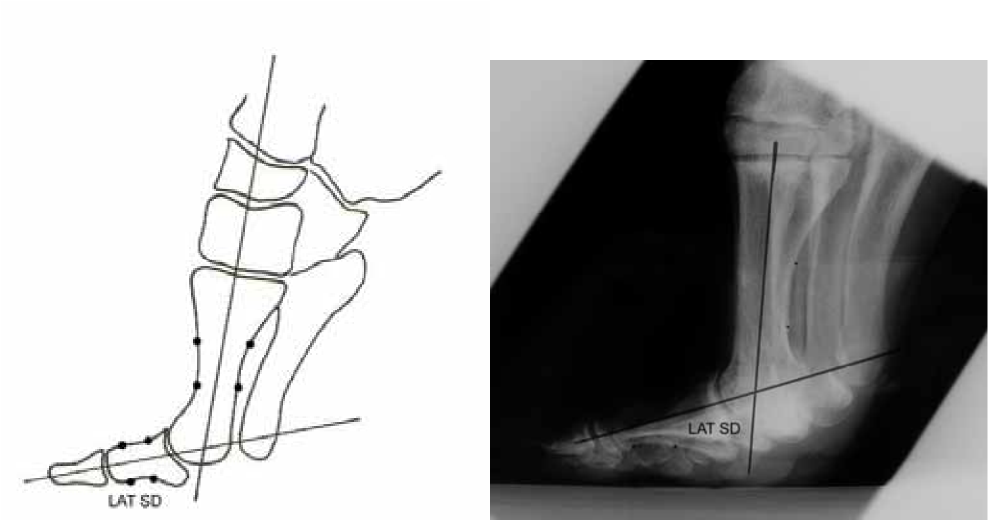

Figure 3.4: Measurement of weight bearing first MPJ dorsiflexion using a weight bearing LAT SD radiograph (adapted from Taranto et al, 2004)[7]

bisected to obtain the point representing the calcaneocuboid joint. A line connecting the two points was drawn and extended distally representing the rearfoot axis. At the anatomical neck of the second and third metatarsals, the medial and lateral cortices were identified and bisected. The distance between these two points was measured and bisected. To obtain a forefoot axis, a line was drawn connecting the point between the second and third metatarsals to the point representing the bisection of the calcaneocuboid joint. The angle between the intersection of the rearfoot axis and the forefoot axis was termed the RFA angle (Figure 3.5).

The LAT view was used to obtain the CIA and LIMA (Figure 3.6). The CIA provides an indication of calcaneal pitch and height of the arch.[5, 52] It is the angle formed by the weight bearing plane and a line drawn from this plane through the anteroplantar margin of the calcaneal tuberosity to the plantar

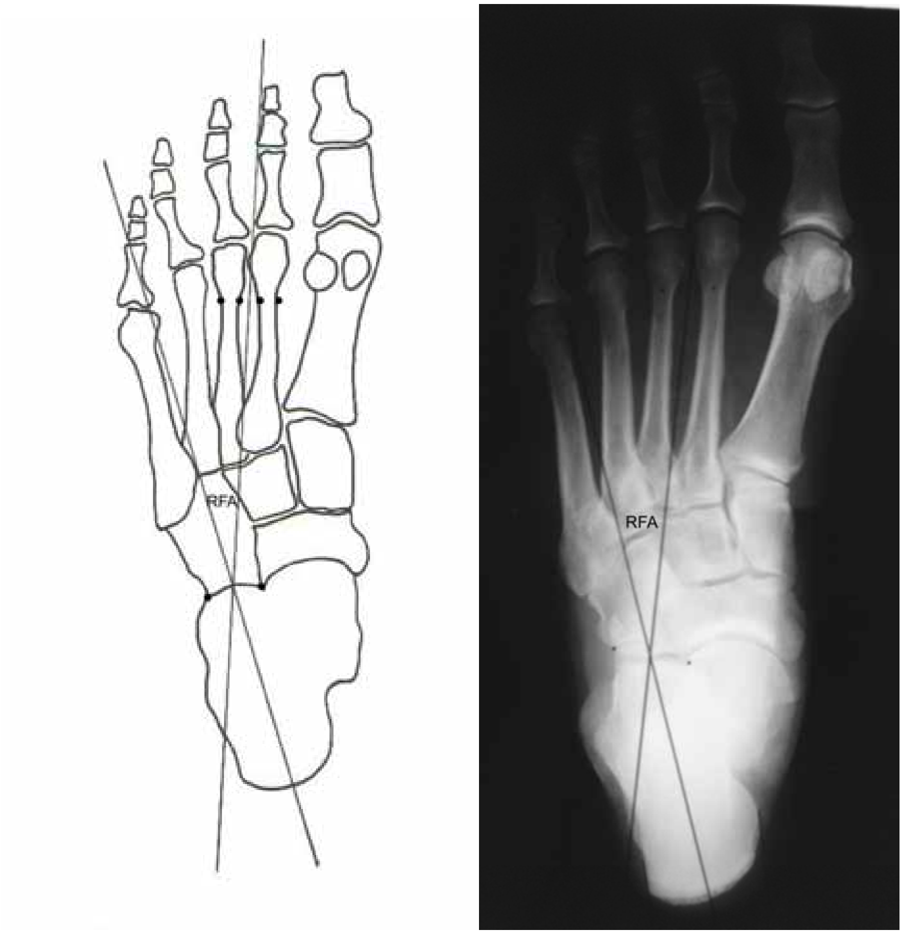

Figure 3.5: Measurement of RFA angle using a weight bearing COMP radiograph (adapted from Taranto et al, 2004)[7]

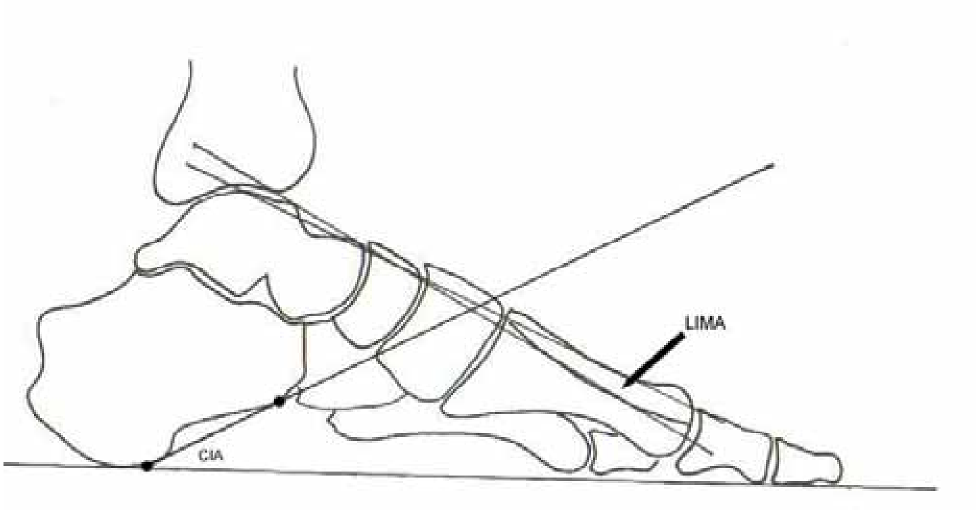

Figure 3.6: Lateral view of the foot showing measurement variables CIA and LIMA (adapted from Taranto et al, 2004)[7]

margin of the anterior portion of the calcaneus. A value of 0°-10° is considered low, 10°-20° medium, and 20°-30° high.[5] For the CIA, a line was drawn representing the weight bearing surface of the foot. Another line was drawn from the antero-plantar margin of the calcaneal tuberosity extending through the plantar margin of the anterior portion of the calcaneus.

The LIMA describes the sagittal plane angular relationship between the first and second metatarsals.[16, 148] For the LIMA, the central region of the dorsal cortex of the first and second metatarsal shafts were marked, with the resultant angle formed by the intersection of these two lines representing the LIMA.

The DP view was used to obtain the HAA, FIMA and FMPD (Figure 3.7). The HAA represents the degree of lateral deviation of the hallux and is the angle formed by the longitudinal axis of the proximal phalanx of the hallux and the longitudinal axis of the first metatarsal. For the HAA, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by these intersecting lines was measured. A normal value is considered less than 20°.[1]

The FIMA is the angle between the longitudinal axis of the first and second metatarsal bones. To calculate FIMA, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified and bisected. This was repeated for the second metatarsal. The angle formed by these intersecting lines was measured. A normal value is between 8-14°.[1]

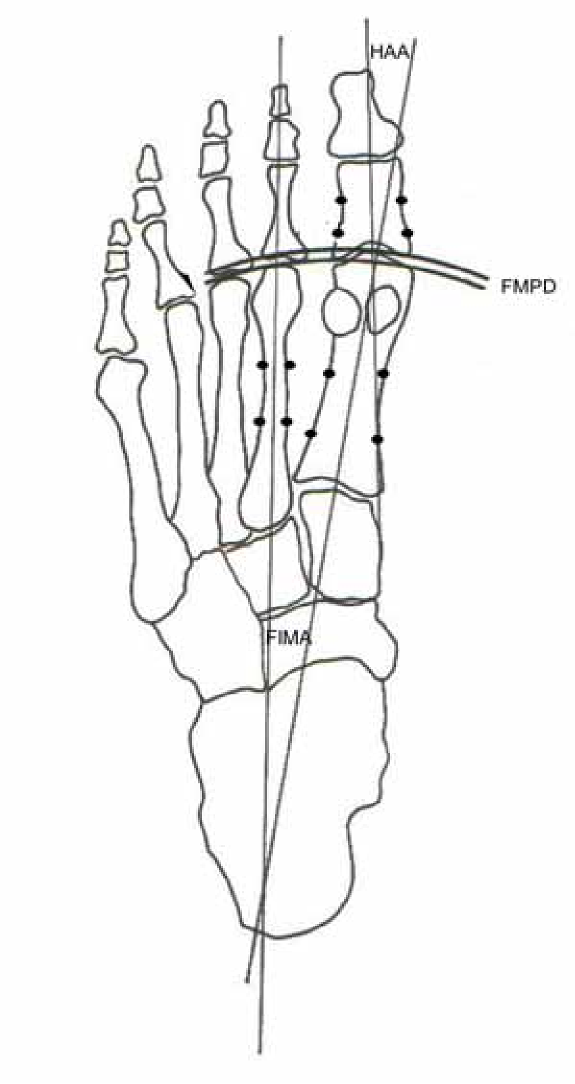

Figure 3.7: DP view of the foot showing measurement variables HAA, FIMA and FMPD (adapted from Taranto et al, 2004)[7]

The FMPD[148] is the distance between the relative length of the first and second metatarsals. Calculation of the FMPD was undertaken with a compass containing a 0.5mm water-soluble felt tip marker as follows. The point of the proximal arm was positioned at the intersection of the FIMA, and a line drawn with the distal arm at the level of the central articulating surface of the first metatarsal head. This line was extended laterally to be in line with the second metatarsal. Keeping the proximal arm of the compass stationary, the distal arm was then positioned at the central articulating surface of the second metatarsal head and a line drawn and extended medially in line with the first metatarsal. The FMPD was the distance between these two lines measured in mm. A positive value denoted the first metatarsal was longer than the second. Conversely, a negative value indicated the first metatarsal was shorter than the second.

3.4.6 Analysis of data

All data were transferred into Statview® (SAS Institute Inc), for descriptive statistical reporting and subsequent analysis. Data obtained for AOG consisted of four footprints, two from the left and two from the right. For the purpose of data analysis, the mean of each side was used. In all tests of statistical significance an alpha level of $P < 0.05$ was adopted.

Most statistical analyses were undertaken using numbers of feet rather than numbers of subjects. The reason for this was to ensure any possible asymmetrical differences were not excluded, and bias was not introduced by averaging the sum of left and right feet, or excluding one of the feet of each subject in the control group. However pooling of left and right foot data may create the potential for both Type I and Type II errors. Essentially, the sample size is doubled and statistically significant differences are more likely to be detected because the confidence limits become smaller (Allison GA 2004, written communication, 2nd August).

A Type I error may arise because of a ‘false positive’, and a Type II error may also occur if one assumes that a non-statistically significant result indicates the two variables are the same.[149] For example, in the present study, some results may not reach statistical significance but by pooling data from both feet, the sample size is increased and therefore the findings may become statistically significant. In order to prevent the possibility of such errors caused by increasing the sample size due to use of numbers of feet rather than numbers of subjects, some analyses were performed based on the number of subjects. Specifically this related to comparison of the subjects who exhibited bilateral HV with the control group.

Of those subjects who had a unilateral HV deformity (5 had right HV, 5 had left HV), their unaffected foot was excluded from the analysis. The rationale for not using the contralateral normal foot in the control group was based on the assumption that subjects with a unilateral pathology may have had an altered AOG between feet due to potential compensatory mechanisms.

3.4.6.1 Normality

The complete data set (HV and control groups combined) and the subgroups (HV and control groups separately) were assessed for normality using the Kolmogorov-Smirnov test. To ensure that normality of the dependent variables was not influenced by an increased sample size due to using numbers of feet, normality testing were undertaken in terms of the use of numbers of subjects.

3.4.6.2 Laterality

Of those subjects who exhibited bilateral HV (thirteen subjects), the data were examined for differences between left and right AOG using paired t tests. Using numbers of subjects rather than numbers of feet, the bilateral HV subjects (n=13) were compared to the control subjects (n=20) to assess for differences between dependent variables. Finally, Pearson's product moment correlation was used to determine whether there was an association between AOG and HAA.

The control group (twenty subjects) was also assessed for differences between left and right AOG. Similarly, paired t tests were undertaken as a separate analysis for those subjects within the sample exhibiting a unilateral HV deformity, even though the contralateral foot without the deformity was excluded from the overall data analysis.

3.4.6.3 Associations

Pearson's product moment correlations were undertaken to detect univariate associations between variables for each subgroup as well as the entire population.

3.4.6.4 Group differences

In order to detect differences in the dependent variables between groups (all HV subjects and all control subjects) unpaired t tests were used. Box plots were used to represent the distribution of these data (Appendix 6). For the purpose of this study, notched box plots were used, indicating the 95% confidence interval around the median.[150]

The variability of normal values of HAA found in the literature provided the rationale for undertaking a tertile analysis which enabled the exclusion of subjects with HAA values close to the HAA threshold, used for allocation into

HV or control groups. Comparison of lower and upper tertiles of HAA was undertaken. Specifically, this involved rank analysis according to HAA threshold whereby HAA values between 15°-25° degrees were excluded. The new sample size consisted of 20 HV feet in the upper tertile, and 34 control feet in the lower tertile. Due to the subsequent reduction in sample size and the unequal number between groups, the non-parametric Mann Whitney U statistic was used. In order to detect whether any of the dependent variables were able to predict inclusion of subjects into one of the two groups, HV or control, a logistic regression procedure was undertaken (Appendix 7). Logistic regression[24] involved allocation of a numerical value, 0 and 1, to the HV and control groups respectively. A logistic regression was then performed on a set of variables.

CHAPTER FOUR

RESULTS

4.0 Introduction

This study investigated AOG characteristics of the feet in a population with and without HV, as determined by degree of HAA. In an attempt to link AOG characteristics to foot structure and function, seven dependent variables were investigated in relation to AOG. These were CIA, LIMA, HAA, FIMA, FMPD, LAT SD and RFA angle. This section provides a summary of the results obtained from statistical analyses. Demographics of the sample population and descriptive statistics for each dependent variable are presented. Emphasis is given to presentation of results on AOG, which are separated from the other dependent variables. Results of analyses to detect univariate associations between variables are provided, followed by investigation of AOG between left and right sides of those subjects with bilateral HV, unilateral HV and control subjects. Finally, results are presented relating to the investigation of differences of the dependent variables between groups.

4.1 Demographics

Demographic data of the sample population are presented in Table 4.1. The entire set of raw data collected are provided in Appendix 8. Descriptive statistics for each dependent variable under investigation excluding AOG are presented for both the HV and control groups in Tables 4.2 and 4.3, respectively. Descriptive statistics of AOG between the HV and control groups is highlighted in Table 4.4, and the AOG of left and right feet between the two groups are represented in Figure 4.1. The control group consisted of 20 subjects

Table 4.1: The mean and standard deviation (SD) of demographic data for the HV and control groups

	N	No. of feet (L, R)	Gender M, F	Age (yrs) (SD) (Range)	Weight (kg) (SD)	Height (m) (SD)	BMI (SD)
HV	23	36 (18,18)	2, 21	61.3 (9.9) (34.0)	66.1 (12.2)	1.6 (0.1)	25.8 (4.4)
Control	20	40 (20, 20)	8, 12	58.8 (15.9) (54.0)	77.1 (9.7)	1.7 (0.1)	28.2 (4.3)

n: number of subjects; No.: number; L: left, R: right; M: male, F: female

Table 4.2: The mean, standard deviation (SD), minimum, maximum and range of dependent variables for the HV group (all measurements are in degrees)

	LEFT		RIGHT	
Dependent Variable	**Mean (SD)**	**Min - Max (Range)**	**Mean (SD)**	**(Min, Max) (Range)**
CIA	23.9 (4.1)	15.0 - 31.5 (16.5)	23.6 (4.0)	(17.0, 31.0) (14.0)
LIMA	3.3 (2.4)	1.0 - 9.0 (8.0)	3.0 (2.7)	(0, 11.0) (11.0)
HAA	27.7 (5.0)	21.0 - 37.0 (16.0)	26.1 (6.3)	(21.0, 45.0) (24.0)
FIMA	12.7 (2.8)	6.5 - 17.0 (10.5)	11.7 (2.4)	(7.5, 18.0) (10.5)
FMPD	2.4 (3.0)	-5.0 - 8.0 (13.0)	0.9 (3.1)	(-5.0, 5.5) (10.5)
LAT SD	56.9 (10.7)	26.0 - 69.0 (43.0)	63.2 (10.2)	(46.0, 85.0) (39.0)
RFA ANGLE	17.4 (6.8)	7.0 - 28.0 (21.0)	16.0 (6.4)	(7.0, 25.0) (18.0)

Min: minimum; Max: maximum (number of subjects = 23, number of feet = 36, 18 left and 18 right, made up of 13 subjects with bilateral HV and 10 subjects with unilateral HV. Of the 10 subjects with unilateral HV 5 had right HV and 5 had left HV)

Table 4.3: The mean, standard deviation (SD), minimum, maximum and range of dependent variables for the control group (all measurements are in degrees)

	LEFT		RIGHT	
Dependent Variable	**Mean (SD)**	**(Min, Max) (Range)**	**Mean (SD)**	**(Min, Max) (Range)**
CIA	25.1 (5.1)	(15.0, 38.5) (23.5)	24.8 (5.3)	(17.0, 38.0) (21.0)
LIMA	2.8 (1.7)	(1.0, 7.0) (6.0)	3.8 (3.1)	(0, 10.0) (10.0)
HAA	9.2 (4.7)	(0, 17.5) (17.5)	10.5 (5.0)	(0, 18.0) (18.0)
FIMA	8.6 (2.7)	(0.5, 13.0) (12.5)	8.5 (1.8)	(5.5, 12.0) (6.5)
FMPD	1.1 (3.8)	(-6.5, 10.0) (16.5)	1.2 (3.4)	(-5.5, 7.0) (12.5)
LAT SD	76.5 (7.1)	(66.0, 87.0) (21.0)	78.2 (7.2)	(66.0, 90.0) (24.0)
RFA ANGLE	19.1 (6.9)	(9.0, 35.0) (26.0)	17.5 (7.1)	(5.5, 35.0) (29.5)

Min: minimum; Max: maximum (number of subjects = 20, number of feet = 40, 20 left and 20 right)

Table 4.4: The mean, standard deviation (SD), minimum, maximum and range of AOG for HV and control groups (all measurements are in degrees)

		AOG (L)		AOG (R)	
	No. of subjects (No. of feet)	**Mean (SD)**	**(Min, Max) (Range)**	**Mean (SD)**	**Min, Max (Range)**
HV	23 (36)	10.4 (5.0)	(2.0, 19.8) (17.8)	13.2 (6.3)	(3.8, 32.5) (28.7)
Control	20 (40)	9.0 (4.7)	(0, 17.0) (17.0)	10.4 (5.1)	(0, 21.5) (21.5)

(L): left foot; (R): right foot; No.: number; Min: minimum; Max: maximum

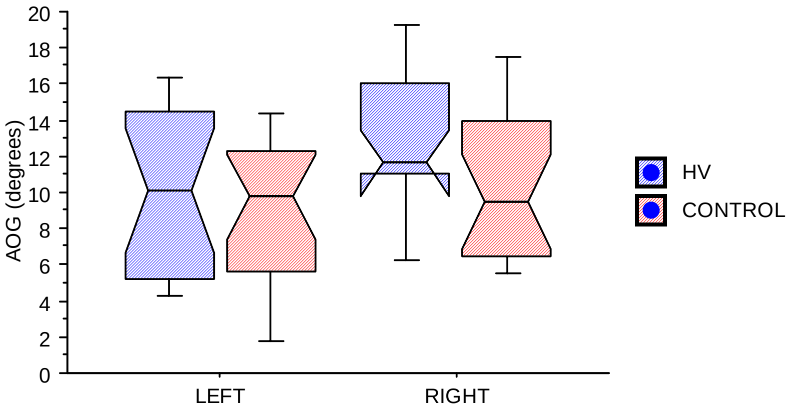

Figure 4.1: Box plot of AOG for left and right feet for HV and Control groups

(40 feet) that could be used in the study as both feet needed to meet inclusion criteria for normal values of HAA. The HV group consisted of 23 subjects (36 feet) made up of 13 subjects with bilateral HV and 10 subjects with unilateral HV. Of the 10 subjects with unilateral HV, 5 had HV on the right foot and 5 had HV on the left foot.

4.2 Normality

Both the subgroups (HV and control groups) and entire sample showed statistical evidence of normality, according to Kolmogorov-Smirnov analysis, (with $P > 0.05$), as presented in Table 4.5. All three groups reported identical *P* values for the dependent variables with the exception of HAA (R), LIMA (L), LIMA (R) and FMPD (L) which were all normally distributed.

4.3 Laterality

A paired t test revealed a significant difference of the AOG between left and right feet for the thirteen subjects in the HV group with bilateral HV (t= -2.63,

Table 4.5: Kolmogorov-Smirnov non-parametric tests for normality for entire sample, HV group and control group

Dependent Variable	**Entire Sample (n= 38 subjects) P value**		**HV (n= 18 subjects) P value**		**Control (n= 20 subjects) P value**	
	L	**R**	**L**	**R**	**L**	**R**
CIA	-	-	-	-	-	-
LIMA	0.24	0.78	-	0.82	0.17	-
HAA	-	-	-	0.82	-	-
FIMA	-	-	-	-	-	-
FMPD	-	-	0.82	-	-	-
LAT SD	-	-	-	-	-	-
RFA ANGLE	-	-	-	-	-	-
AOG	-	-	-	-	-	-

(-): *P*>0.99; L: left foot; R: right foot

P=0.02), as demonstrated in Figure 4.2. The twenty subjects in the control group showed no significant difference in the AOG between left and right feet (t=-1.13, *P*=0.27). Similarly, no significant difference was found for AOG between left and right feet for the ten subjects in the HV group with unilateral HV (t=0.85, *P*=0.42).

An unpaired t test showed a significant difference (t=2.43, *P*=0.02) in AOG of the right foot between the subjects who exhibited bilateral HV (n= 13 subjects) and the control group (n= 20 subjects), as seen in Figure 4.3. Pearson's product moment correlation between the group which exhibited bilateral HV and the control group showed no association between AOG and HAA (R: 0.18, CI:-0.06, 0.41).

An unpaired t test showed no significant difference (t=0.44, *P*=0.66) in the AOG of the left foot between the subjects who exhibited bilateral HV (n= 13 subjects)

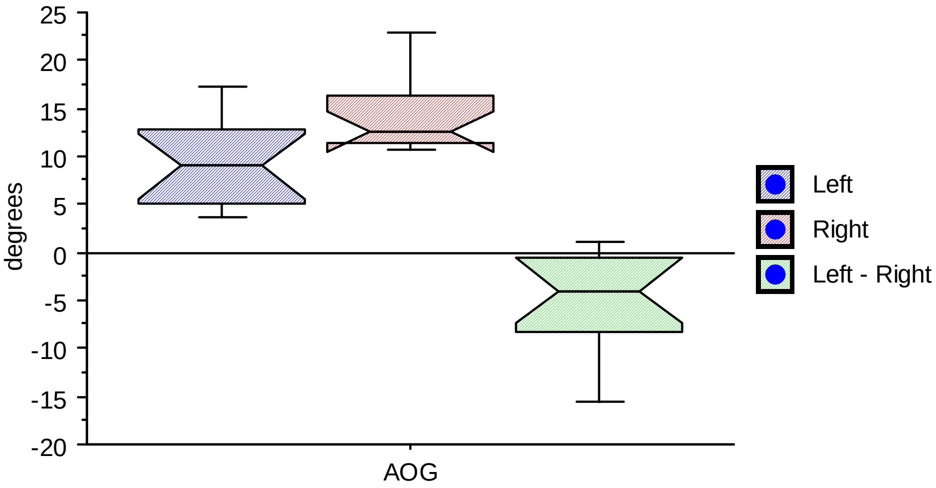

Figure 4.2: Box plot showing AOG between left and right feet and distribution of the difference between left and right sides of AOG for the thirteen subjects with bilateral HV

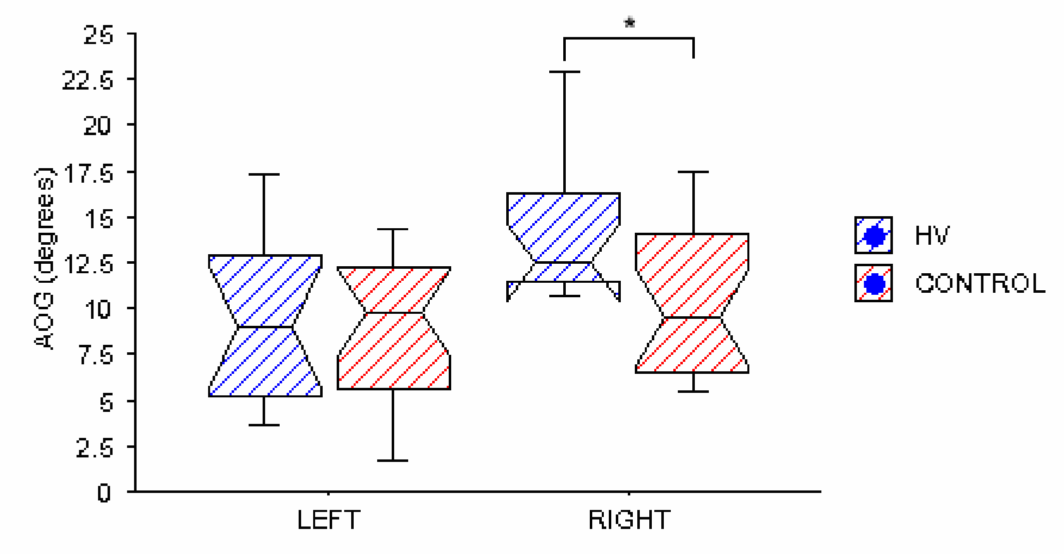

Figure 4.3: Box plot showing difference of AOG of the right and left feet between subjects with bilateral HV (n=13) and the control group (n=20); *significant difference (*P* < 0.05)

and the control group (n= 20 subjects).

4.4 Associations

Results of Pearson’s product moment correlations for the subgroups and entire sample are presented in Appendix 9. The significant associations found for each subgroup and the entire sample are shown in Table 4.6.

4.5 Group differences

Unpaired t tests between the HV and control groups are presented in Table 4.7. Significant differences between groups were found bilaterally for the dependent variables HAA, FIMA and LAT SD. This was also seen in the tertile assessments using non-parametric rank analysis and Mann Whitney U statistic, in which HAA between 15°-25° were excluded, as seen in Table 4.8. Given that HAA was the dependent variable used to classify the rank analysis it was not included in the results. Significant findings for FIMA and LAT SD are presented as box-plots in Figure 4.4 and Figure 4.5, respectively.

Table 4.6: Significant Pearson's product moment correlations between dependent variables for HV group, control group and entire sample ($P < 0.05$)

Association	Correlation	95% lower CI	95% upper CI
<u>HV Group</u>			
LIMA & FIMA	-0.49	-0.71	-0.20
LIMA & FMPD	0.50	0.21	0.71
FIMA & LAT SD	0.41	0.10	0.65
FIMA & RFA ANGLE	-0.41	-0.65	-0.10
FMPD & LAT SD	-0.37	-0.62	-0.04
<u>Control Group</u>			
CIA & LAT SD	0.32	0.00	0.57
LIMA & FIMA	-0.33	-0.58	-0.02
HAA & FIMA	0.33	0.02	0.58
FIMA & FMPD	-0.39	-0.62	-0.08
<u>Entire Sample</u>			
CIA and LAT SD	0.23	0.01	0.43
LIMA & FIMA	-0.35	-0.53	-0.13
LIMA & FMPD	0.36	0.14	0.54
HAA & FIMA	0.64	0.48	0.75
HAA & LAT SD	-0.59	-0.72	-0.41
FIMA & LAT SD	-0.27	-0.46	-0.04

Table 4.7: T values, *P* Values, 95% lower and upper confidence intervals (CI), and mean difference for dependent variables between HV and control groups obtained from unpaired t tests

Dependent Variable	T value		*P* value		95% lower CI		95% upper CI		Mean Difference	
	L	R	L	R	L	R	L	R	L	R
CIA	-0.75	-0.76	0.46	0.46	-4.19	-4.29	1.93	1.97	-1.13	-1.16
LIMA	0.72	-0.88	0.48	0.39	-0.87	-2.77	1.84	1.10	0.48	-0.84
HAA	11.74	8.44	-	-	15.32	11.84	21.72	19.33	18.52	15.58
FIMA	4.61	4.64	-	-	2.32	1.80	5.97	4.59	4.15	3.19
FMPD	1.12	-0.24	0.24	0.81	-0.94	-2.38	3.58	1.87	1.32	-0.26
LAT SD	-6.72	-5.25	-	-	-25.50	-20.74	-13.68	-9.17	-19.59	-14.96
RFA ANGLE	-0.78	-0.68	0.44	0.50	-6.26	-5.97	2.79	2.96	-1.74	-1.50
AOG	0.86	1.54	0.40	0.13	-1.85	-0.91	4.55	6.60	1.35	2.84

L: left foot; R: right foot; "-": $P < 0.0001$; =18 feet in HV group per left and right side, n=20 feet in control group per left and right side

Table 4.8: *P* values and z values from Mann Whitney U rank analysis with and without tertile assessment

Dependent Variable	**No Tertile Assessment** ***P* value (z value)**	**Tertile Assessment** ***P* value (z value)**
CIA	0.50 (-0.68)	0.84 (-0.21)
LIMA	0.77 (-0.29)	0.42 (-0.81)
FIMA	**<0.0001** (-5.51)	**<0.0001** (-4.96)
FMPD	0.39 (-0.86)	0.24 (-1.18)
LAT SD	**<0.0001** (-6.3)	**<0.0001** (-5.02)
RFA ANGLE	0.39 (-0.87)	0.35 (-0.94)
AOG	0.13 (-1.51)	0.43 (-0.80)

No Tertile Assessment: no exclusion of HAA threshold, n=36 HV feet, 40 control feet; Tertile Assessment: HAA threshold exclusion 15°-25°, n=20 HV feet in upper tertile, 34 control feet in lower tertile; significant values are presented in bold

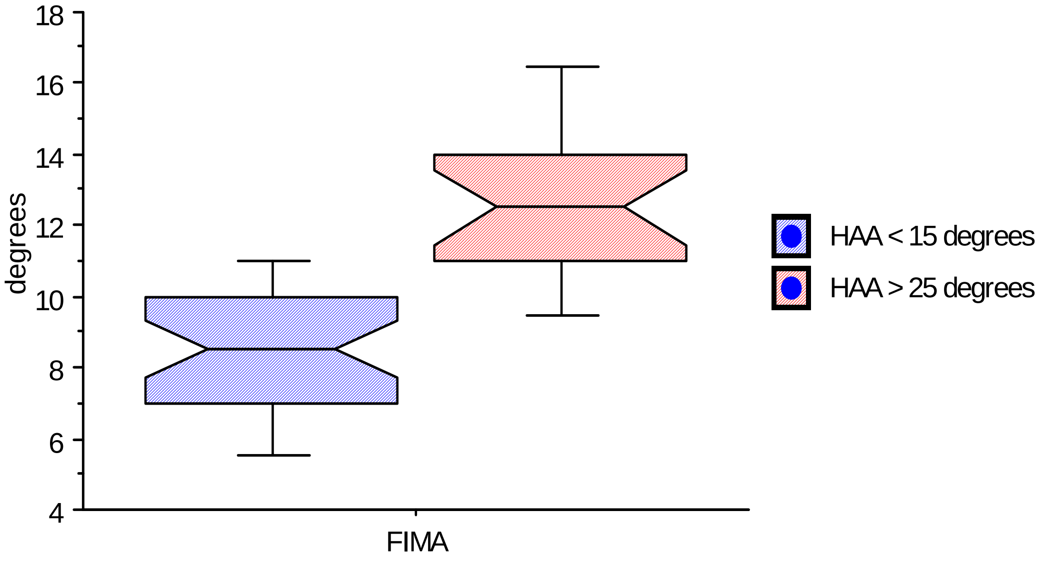

Figure 4.4: Box plot of actual values of FIMA for the lower and upper tertiles based on HAA threshold (HAA threshold exclusion15°-25°)

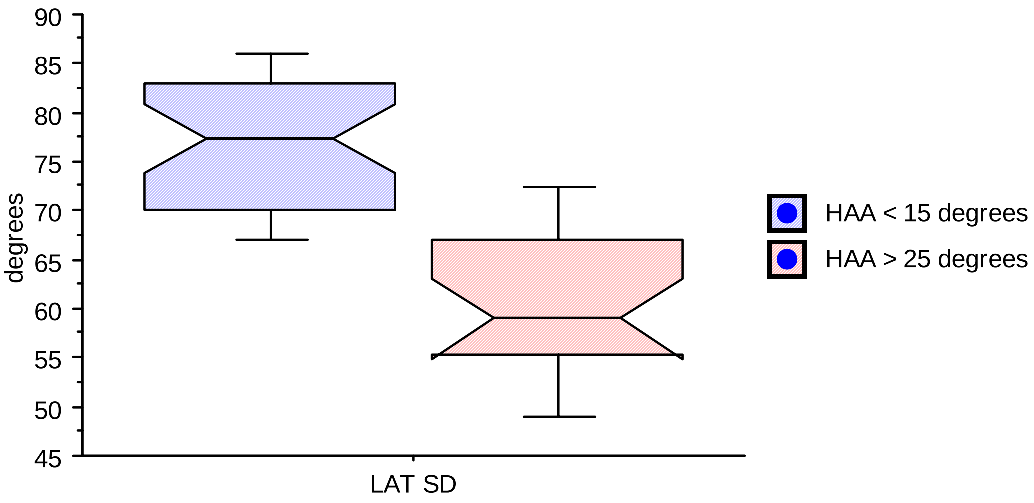

Figure 4.5: Box plot of actual values of LAT SD for the lower and upper tertiles based on HAA threshold (HAA threshold exclusion15°-25°)

CHAPTER FIVE

DISCUSSION

5.0 Introduction

This study was undertaken in an attempt to determine whether AOG characteristics were different between subjects with and without HV. The impetus for this investigation was the result of clinical suspicion and findings within the literature which would imply that abnormal foot mechanics are associated with pathology. The literature identified variability in the normal reference range for AOG.

The Chapter begins with an assessment on normality of the sample population with regard to the dependent variables. This is followed by discussion of results of the study with specific reference to individual hypotheses (i – iv), formulated at the initiation of this research process. Specifically, these related to reliability of measurements, AOG, characteristics of the first metatarsal, first MPJ dorsiflexion, rearfoot to forefoot abduction, foot structure and unilateral pathology. A pictorial representation of associations between dependent variables for the entire sample is provided in Figure 5.1, in an attempt to provide a diagram to refer to during the discussion. Normal reference ranges for HAA and AOG is discussed based on the findings of this study. The dependent variables that are statistically different are discussed. Finally, limitations of the study and recommendations for future investigations are presented.

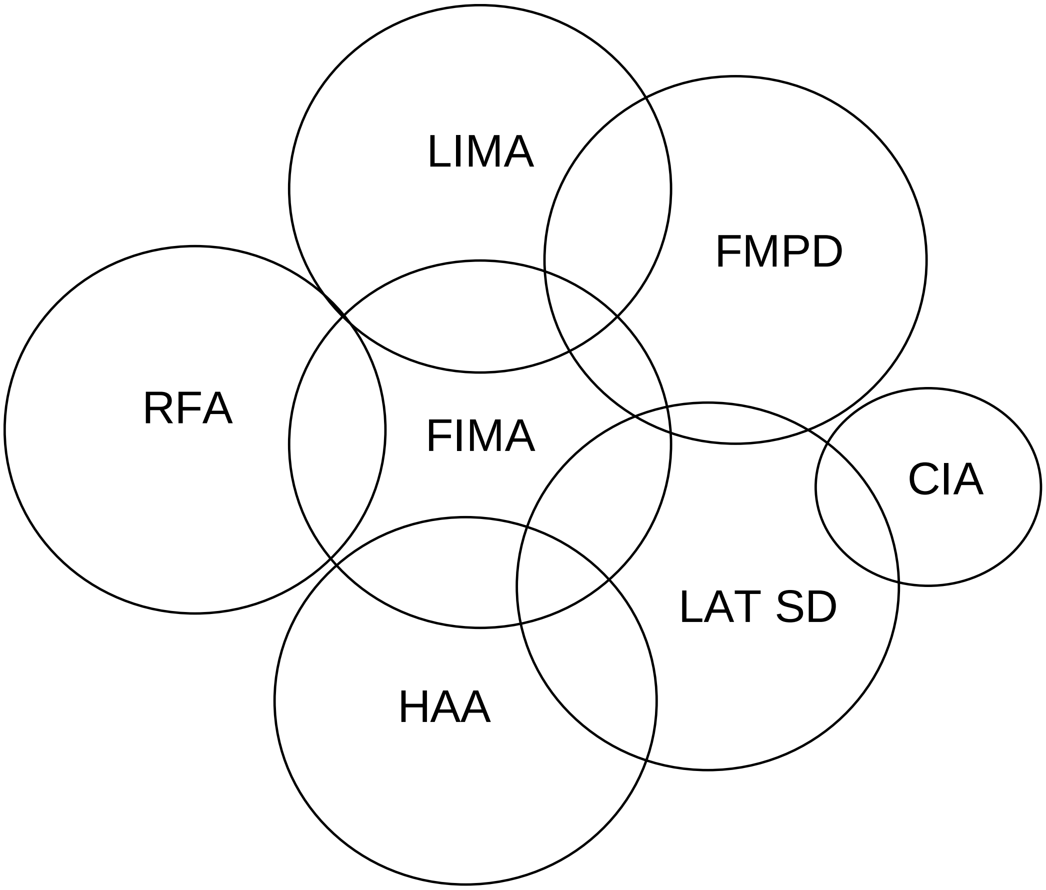

Figure 5.1: Venn diagram showing associations between dependent variables for the entire sample; AOG is not featured, as the only significant association for AOG occurred in the control group only, whereby it was associated with CIA

5.1 Normality

Statistical analysis showed the entire sample and the subgroups to be normally distributed, however some differences in normality between groups were found for the dependent variables HAA, LIMA and FMPD. This result was expected for HAA as this was the variable used to classify the groups. The results also indicated there was less probability that LIMA and FMPD were normally distributed in the HV group. The role metatarsal elevation plays in deformity of the first MPJ is a controversial issue within the literature. Some authors supported a relationship between an elevated first metatarsal and first MPJ deformity[16, 77, 78] as measured by LIMA. One study identified a significant difference between angular divergence of the dorsal cortices of the first and second metatarsal shafts between normal and HL feet,[16] although values were not placed on the magnitude of the relationship. However other investigators have suggested metatarsal elevation may not necessarily be related to first MPJ deformity.[46, 76] Similarly, the presence of a long first metatarsal associated with HV has also been debated in the literature. The results of normality tests for HAA, LIMA and FMPD did not imply an association between variables, but simply a difference in the probability of the variables being normally distributed between the HV and control groups.

5.2 Research questions

5.2.1 Reliability of measurements

(i) Was AOG measured from powdered footprints reliable?

(ii) Could the AOG obtained from powdered footprints be compared to the FPA derived from the EMED-SF® pressure platform?

(iii) Were the seven specific radiographic weight bearing angular and linear measurements to be used reliable?

The first three hypotheses were addressed by pilot studies undertaken prior to the investigation, as presented in sections 1.1.1 and 1.1.2 of Chapter One. Results of the pilot studies[6, 7] (Appendices 1, 2) confirmed the methodology of obtaining the AOG used in the current investigation was reliable, and was comparable to the FPA obtained from the EMED-SF® pressure platform. Specifically, intra-rater reliability ranged between 0.93 to 0.95, and inter-rater reliability of 0.93. The typical error (0.95) indicated test retest reliability would provide values to within one degree of each rater, on 95% of occasions.[6]

Similarly, the seven specific radiographic weight bearing angular and linear measurements derived were reliable. Intra-rater reliability of the group of radiographic measurements as assessed by Pearson's product moment correlation ranged between 0.83 – 0.99 for rater 1, and 0.65 – 1 for rater 2, between trials 1 and 2. Analysis of paired t tests showed no statistically significant difference between raters for LAT SD, RFA angle, FIMA, LIMA and FMPD. The only dependent variable that reported a statistically significant difference (t = -3.32, P = 0.002) between the two raters was CIA with rater 2 scoring on average 0.94 lower than rater 1 (95%CI: -1.52, -0.37).[7]

5.2.2 Angle of gait

(iv) Did subjects with HV have a more abducted AOG when compared to the control group?

In order to address this hypothesis, it was first necessary to detect whether differences were present when comparing AOG of the same subject between left and right feet. Results of the study showed a significant difference of AOG between the left and right feet of the thirteen subjects with bilateral HV, whereby the right was more abducted (t=-1.13, P= 0.27). No difference was found in the control group. When the thirteen subjects with bilateral HV were compared to the twenty control subjects, there was also a significant difference (t=2.43, P= 0.02) of AOG between the left and right feet, with the right foot being more abducted. This asymmetry may relate to issues of dominance[151, 152] however it is speculative as information relating to dominance was not included in the subject profile. However, it may be possible that bilateral pathology alters AOG more than unilateral pathology as the person with HV may have a more mechanically unstable gait, which may in turn lead to compensatory increases in AOG, and perhaps base of gait. An abducted foot position and wide base of gait is assumed by people who require increased stability, such as toddlers and the elderly.[86, 153, 154]

When the bilateral HV subjects were compared to the control group, no association was identified between AOG and a greater HV deformity. That is, AOG did not increase as HAA increased (R: 0.26, CI: -0.09, 0.56). This may be considered to be in contrast to the cited literature which suggested abnormal pronation as a cause of HV.[21, 25, 32-36] However, this is only feasible if one accepts the assumption that AOG is reflective of foot type and degree of pronation. If an increased AOG was not associated with a more advanced HV deformity, the larger abduction found in the right foot may be due to some other factor, such as dominance. The fact that the right foot was more abducted than the left does not help answer the question of whether HV is a causative factor of an abducted AOG when it is observed or is a compensatory mechanism.

5.2.3 First metatarsal characteristics

(v) Did subjects with HV have a longer, shorter or elevated first metatarsal when compared to the control group?

The results of this study did not show an association between HV, as measured by HAA, and the presence of a long or short metatarsal. This was in contrast to the findings of some authors[38, 46, 79] but in support of Saragas and Becker[72] and Villadot.[39] Instead, an association was seen between FMPD and LIMA in the HV group (R: 0.50, CI: 0.21, 0.71), and this association was also significant when the entire sample was included (R: 0.36, CI: 0.14, 0.54). This may imply that length of the metatarsal is related to whether or not the metatarsal becomes elevated. It may also have implications relating to x-ray distortion.[113] For example, does the first metatarsal look and measure longer than the second, or is it simply an artifact due to x-ray magnification and distortion? This has been tested in the literature, with Camasta et al[113] providing conversion factors for selected metatarsals to correct for x-ray distortion. The present study did not apply conversion factors to counteract radiographic magnification and distortion, however all radiographs were standardised and it was therefore considered that any magnification would be consistent between subjects.

An interesting finding was that FIMA was associated with LIMA in all three groups, namely the HV group (R: -0.49, CI: -0.71, -0.20), control group (R: -0.33, CI: -0.58, -0.02), and the combined sample (R: -0.35, CI: -0.53, -0.13). As FIMA increased, LIMA decreased. This was in agreement with Ìncel[50] who proposed that an elevated first metatarsal was an aetiological factor for HV.

The association between FIMA and HAA noted in the literature met with mixed results the present study. The entire sample showed an association between FIMA and HAA (R: 0.64, CI: 0.48, 0.75), as did the control group (R: 0.33, CI: 0.02, 0.58). Interestingly however, the HV group did not show a significant association between these two variables. An unpaired t test found a significant difference in HAA and FIMA ($P< 0.0001$) between the HV and control groups. It was only when the HV subjects were combined with the control subjects that the association became evident. That is, even though there was a difference in the means of HAA and FIMA between the HV and control groups, the lack of association between FIMA and HAA in the HV group indicated that even by knowing the value of one of the variables, it was not possible to confidently predict the value of the other. The results therefore suggested that in the sample tested, despite literature support for an increased FIMA and the presence of HV, there was no way of predicting one of the variables based on the other.

Normal values for FIMA, obtained from the control group in this study were a mean (±SD) of 8.6° (±2.7°) and 8.5° (±1.8°) for the left and right feet, respectively. This was consistent with the literature that reported normal FIMA was less than or equal to 9°.[74]

In the HV group, FMPD was also significantly associated with LAT SD (R: -0.37, CI: -0.62, -0.04) suggesting that the length of the metatarsal may have implications regarding first MPJ range of motion. With a longer metatarsal, more ‘jamming’ occurs at the first MPJ, and the subsequent decrease in first MPJ dorsiflexion, as supported in the literature.[77, 155]

In the control group, FMPD was associated with FIMA (R: -0.39, CI: -0.62, -0.08), indicating that length of the metatarsal is related to the first intermetatarsal angle. This relationship indicates that the longer the metatarsal, the smaller the first intermetatarsal angle. Anecdotally this may indicate that a long first metatarsal is not associated with HV that has an increased first intermetatarsal angle as supported by Saragas and Becker[72], but perhaps is more important for HL,[77, 155, 156] a condition that is not associated with an increased FIMA.[157-159]

An association was found between LIMA and FIMA for the HV group (R: -0.49, CI: -0.71, -0.20), the control group (R: -0.33, CI: -0.58, -0.02), and the combined sample (R: -0.35, CI: -0.53, -0.13). This implied that as FIMA increased, elevation of the first metatarsal decreased. This suggests that a long first metatarsal may not necessarily be a precursor to HV.

5.2.4 First metatarsophalangeal joint dorsiflexion

(vi) Did the amount of first MPJ dorsiflexion influence AOG in subjects with HV when compared to the control group?

Review of the literature supported the concept of first MPJ deterioration and pathology associated with increased severity of HV as represented by an increased FIMA. This study supported this, finding an association between FIMA and LAT SD (R: 0.41, CI: 0.10, 0.65) in the HV group but not in the control group. The entire sample also showed this association (R: -0.27, CI: -0.46, -0.04) suggesting that as first MPJ limitation of motion decreased, FIMA increased. The different directions in the association of the HV group and entire sample indicated there may be a non-linear association between the two variables FIMA and LAT SD. The entire sample also showed an association between HAA and LAT SD (R: -0.59, CI: -0.72, -0.41). This indicates that as the HV deformity worsened, less dorsiflexion was available at the first MPJ.

According to the literature, a value of 65° or more was considered necessary for normal function of the first MPJ.[71] The control group supported this by exhibiting a LAT SD mean of 76.5° and 78.2° for the left and right foot respectively. In contrast, the HV group had a mean of 56.9° and 63.2° for the left and right foot respectively. This highlights the relationship between HV pathology and decrease in first MPJ dorsiflexion. Another question arises, as to whether these values of LAT SD are pathological.

An association was found between CIA and LAT SD in the control group (R: 0.32, CI: 0.004, 0.57) and entire sample (R: 0.23, CI: 0.01, 0.43), indicating that first MPJ dorsiflexion was increased in subjects with a higher calcaneal inclination angle. This is an indirect measure of arch height and depicts a higher arch type. This was in contrast to literature support for excessive pronation as a cause of pathologies affecting the first MPJ, specifically hallux limitus.[68-70] This is under the assumption that pronation is an indicator of foot structure as measured by CIA[5].

5.2.5 Rearfoot to forefoot abduction and foot structure

(vii) Did AOG reflect the amount of rearfoot to forefoot abduction in a foot with HV compared to the control group?

(viii) Did AOG become more abducted as the arch of the foot became lower in subjects with HV compared to the control group?

According to the literature, excessive pronation has been implicated as a cause of HV.[21, 25, 32-36] The radiographic measures relating to foot pronation and subsequent abduction used in the study were CIA and RFA angle. In order to determine whether excessive pronation was related to HV, investigation of AOG as it related to CIA and RFA angle was undertaken.

If excessive pronation, as indicated by CIA, was related to forefoot abduction, one would expect in the HV group, that as CIA increased and the arch of the foot became higher, AOG would decrease. This did not occur however, and may suggest that CIA should not be used as a measure of foot function, specifically pronation.[55] It is also possible that decreased arch height is not always associated with abduction of the foot, and may instead result in abduction of the forefoot on the rearfoot, as indicated by Bojsen-Moeller.[133] This concept would be also supported by Neylon et al[48] who demonstrated arch collapse without excessive abduction of the forefoot. It also highlights the importance of planal dominance as explained by Green and Carol,[138] suggesting the degree of compensation within a foot will take place in the plane with most available motion for that particular foot. Consideration must also be given to CIA as a static radiographic measurement whereas pronation represents dynamic foot function.

A relationship was not seen between RFA angle and AOG. This may have indicated that either the amount of rearfoot to forefoot abduction was not associated with AOG, or that because it was such a small value, RFA angle was not a sensitive enough measurement to detect larger variations in AOG.

An association was found between FIMA and RFA angle (R: -0.41, CI: -0.65, -0.10) suggesting the more adducted the forefoot is on the rearfoot, the smaller the value of FIMA. This finding may also lend support to published literature suggesting an association between metatarsus adductus and HV.[21, 50, 61, 135]

5.2.6 Unilateral pathology

(ix) Did AOG differ significantly between feet in subjects with unilateral HV?

The observation that AOG was not affected by the degree of HV was further supported by the results of a paired t test which showed the means of AOG were not different between left and right feet of the ten subjects who exhibited a unilateral HV deformity (t= 0.85, *P*= 0.42).

5.3 Variability of the hallux abductus angle

Literature suggested some discrepancy regarding values considered normal for HAA. Results of this study showed normal values of HAA, based on the control group, as ranging from 0°-17.5° for the left foot (mean 9.2°), and 0°-18° on the right foot (mean 10.5°). Certainly the mean of HAA in the control group was similar to those authors who suggested a value less than 5° was normal.[5, 23, 60, 61] Pathological HAA as represented by the HV group, reported HAA values ranging from 21°-37° for the left foot (mean 27.7°), and 21°-45° for the right foot (mean 26.1).

5.4 Variability of angle of gait

In support of the literature, this study showed a large variation for normal ranges of AOG in the control group, with a mean (±SD) of 9.0° (±4.7°) for the left foot and 10.4° (±5.1°) for the right foot. There was a very large range of values, from 0°- 21.5°, even larger than the range of 5°-13°[9, 71, 83, 84 85, 86] found in the literature. Furthermore, the range of AOG for the HV subjects was also very large (2°- 28.7°) and not significantly different from the control group. It is possible the large variability in AOG was perhaps largely responsible for the lack of significant differences between the HV and control groups.

5.5 Significant findings of dependent variables

Results of unpaired t tests for dependent variables between HV and control groups expectedly showed significant differences (*P*<0.0001) for left and right values of HAA, FIMA and LAT SD.

Based on the rationale that extreme values of HAA may have been required to determine differences clinically, use of tertile assessments were used. Tertile assessment involved ranking of the data in order from the lowest to the highest value of HAA, and excluding HAA values between 15°-25°. Mann Whitney U interpretation was used and revealed significant findings for FIMA (*P*<0.0001) and LAT SD (*P*<0.0001). Once again, this supported the concept that the two radiographic variables most indicative of HV were the best predictors of them, thereby advocating the inclusion criteria for HV and control subjects used in this study. This was also replicated by results of the logistic regression analysis that created a hierarchy which replicated the findings of the significant P values for FIMA and LAT SD found in both the tertile and non-tertile assessments (Appendix 7). The critical predictive values were found to be HAA, LAT SD and FIMA.

5.6 Limitations and recommendations for further study

There were some limitations identified in this study that have enabled recommendations to be made for further investigation on this topic.

The lack of significant findings in the dependent variables between the HV and control groups may have been related to size and gender demographics of the sample population. Despite the HV and control groups containing similar numbers and means with regard to age distribution, the few age-matched females in the control group, was a limitation, particularly given that HV is more prevalent in females than males.[14] Further studies should seek to match the pathological and control groups with regard to age and gender more closely.

The range for normal values of AOG is larger than those reported in the literature.[9, 71, 83-86] Certainly, this study cohort exhibited a large range. This would mean there is difficulty in identifying differences in AOG between groups, particularly given the many extrinsic factors that can affect AOG. Increasing the sample size and further studies of AOG in normal populations would assist this purpose. Specifically, a longitudinal study[160] would be recommended, with a study cohort divided into decades, such that the effect of age can be assessed,[86, 153, 154] and an attempt made to quantify the relative contribution to AOG from soft tissue osseous and torsional changes at the hip, knees and ankles, respectively.

A recommendation for further studies would be to include information pertaining to dominance of feet, alluded to in the literature by Clarkson.[87] This is in light of the asymmetrical findings between right and left feet in the present study. Angle of gait may have displayed a tendency for the right foot to be more abducted than the left. However this is speculative in the absence of information relating to dominance. Additionally, measurement of leg length would be indicated, due to functional changes that manifest during gait.[161] The lack of a significant difference in AOG for the ten subjects with unilateral pathology cannot warrant interpretation in such a small sample. A larger sample with equal numbers of subjects exhibiting bilateral and unilateral pathology would be desirable. Finally, in the present study, consideration must also be given to the fact that AOG, a dynamic measurement, was compared to dependent variables measured from static weight bearing radiographs.

A further recommendation for future investigations regarding AOG and HV would be to include specific information relating to symptomatology. That is, do HV subjects with symptoms have different characteristics to those without symptoms? Perhaps increased abduction is a compensatory mechanism for pain rather than for the foot deformity itself? Similarly, incorporation of a grading system on limb and overall body balance[91] would be useful on the basis that an abducted AOG is representative of the need for increased stability.[86, 153, 154]

Utilisation of a computerised system, for example RSscan® (RSscan International, Olen, Belgium), allowing subjects to walk for a long period of time without interruption would be desirable. Although expensive, such systems enable data collection on a number of parameters, including speed, force, pressure, angle and base of gait, and, enable a greater number of subjects to be tested in a more time efficient manner. Finally, a motion analysis system could be used to collect additional information on kinematic parameters of the lower extremity.

CHAPTER SIX

CONCLUSIONS

6.0 Introduction

This Chapter presents the conclusions of the study, grouped according to the original research questions (i – iv).

6.1 Conclusions

From this study, the following conclusions, limited to this cohort, may be drawn:

Reliability:

(i) Angle of gait measured from powdered footprints was reliable.

ii) Angle of gait obtained from powdered footprints was comparable to the FPA derived from the EMED-SF® pressure platform.

iii) The radiographic dependent variables CIA, LIMA, HAA, FIMA, FMPD, LAT SD, and RFA angle, as derived, were reliable.

Angle of gait:

iv) Subjects with HV (unilateral HV and bilateral HV combined) did not have a more abducted AOG when compared to the control group. Subjects with bilateral HV showed a significant difference of AOG between left and right feet; the right foot was more abducted. Subjects in the control group did not show a difference of AOG between the left and right feet. Subjects with bilateral HV showed a significant difference of AOG between left and right feet when compared to the control group; the right foot was more abducted. AOG was not associated with degree of HV deformity.

Length and elevation of first metatarsal:

v) Subjects with HV did not show an association between FIMA and HAA until they were combined with data from the control group and analysed as an entire sample. Subjects with HV did not have a long, short or elevated first metatarsal when compared to the control group. Subjects with HV showed an association between length and elevation of the first metatarsal. Subjects with HV showed an association between FMPD and LAT SD.

First MPJ dorsiflexion:

vi) The amount of first MPJ dorsiflexion did not influence AOG in subjects with HV when compared to the control group. Subjects with HV showed an association between FIMA and LAT SD.

Rearfoot to forefoot abduction:

vii) Angle of gait did not reflect the amount of rearfoot to forefoot abduction in the foot with HV compared to the control group.

Angle of gait and arch height of the foot:

viii) Angle of gait did not become more abducted as the arch of the foot became lower, as indicated by CIA, in subjects with HV compared to the control group.

Angle of gait and unilateral pathology:

ix) Angle of gait did not differ between left and right feet in subjects with unilateral HV.

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Appendix 1:

Angle of Gait: A Comparative Reliability Study Using Footprints and the EMED-SF®

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SUMMARY

Background: Gait analysis using footprint impressions is a simple and inexpensive method of obtaining valuable information relating to foot dynamics.
Objectives: To assess the reliability and comparability of two different measurement techniques to quantify angle of gait (AOG).
Method: Part 1. Two observers measured angle of gait (AOG), in six asymptomatic adult subjects, three times at weekly intervals. Part 2. A comparison of AOG from powdered footprints, and foot progression angle (FPA), the equivalent to AOG, derived from the EMED-SF® force platform were simultaneously compared using 11 asymptomatic adult subjects.
Results: A Pearson's product moment correlation of 0.94 for rater 1 and 0.93 for rater 2 was observed between trials 1 and 2. Between trials 2 and 3, a Pearson's product moment correlation of 0.95 was observed for rater 1 and rater 2. The mean difference was 0.26 (CI: -0.06, 0.57), indicating no significant difference (*t* = -1.63, *P* = 0.108). A Pearson's product moment correlation of 0.98 for AOG from powdered footprints and FPA from EMED-SF® was observed with a mean difference of 0.03 (CI: -0.54, 0.59), indicating no significant difference (*t* = 0.09, *P* = 0.93). Assessment of agreement using the Bland and Altman statistical model reflected moderate differences between raters and techniques of measuring AOG.
Conclusions: Calculation of AOG from powdered footprints is a reliable and repeatable method, also demonstrating comparability to the FPA derived from the EMED-SF® platform.
Keywords: Gait analysis, angle of gait, foot progression angle, powdered footprints, EMED-SF®.

INTRODUCTION

The term angle of gait (AOG) refers to the mid-sagittal position of each foot in midstance relative to the direction of forward movement during gait.[1] Angle of gait has demonstrated a highly variable normal reference range of between 5° to 9°[2-4] and 7.5° to 10° abducted from the midline of forward progression.[5] Furthermore, AOG may also be influenced by walking speed, and it has been suggested the dominant leg may be a factor in the amount of abduction occurring during gait.[6] Additionally, tactile feedback derived from the walking substrate and amount of friction on the walkway have been thought to be important.[6, 7] Factors proposed to influence angle of gait include hip joint motion, tibial and malleolar torsion and, adduction or abduction of the foot.[7]

There have been numerous studies looking at measurement of gait parameters. One particular study measured step length and step width using video and a grid system on a walkway, concluding valid and reliable measurements could be obtained.[8] A variety of techniques have been used, including plaster of Paris, adhesive corn plasters, talcum powder, gauze injected with ink, moleskin, force platforms, absorbent paper, glass plates, video and motion analysis systems.[6, 8-19]

Most AOG studies have involved measurement relative to a line through the middle of a walkway.[7] More recent investigators believed this was not reflective of normal walking, under the assumption the line of progression changed during the gait cycle.[1] Other studies have calculated the line of progression by using ipsilateral footprints,[20] however this may not account for the variability in the line of progression caused by the contralateral foot.[1]

The footprint method of assessing gait parameters has been shown to be easy, reliable, valid, inexpensive and clinically feasible.[6, 14, 16, 20, 21] A recent study investigating the variability in outlines of barefoot inked footprints for forensic purposes showed large variability between subjects and a high degree of similarity for multiple impressions from the same subject.[22] However, variability was examined between subjects from an identification viewpoint, with regard to foot dimensions, concluding inked footprints are highly individual.

Few studies have investigated the simultaneous collection of footprint data, and none have investigated the simultaneous comparison of powdered footprint and EMED-SF® (novel, gmbh, Munich, Germany) data. Urry and Wearing[23] compared ink footprints to electronic footprints as a means to assess differences in geometric parameters. Intra-rater reliability of geometric analysis of electronic footprints have been reported to be high.[24] Potential problems associated with electronic footprints are poorly delineated and irregular borders[25] and inadequate contact area as a result of equipment sensitivity.[23]

The EMED-SF® force platform analysis system is an instrument used for recording and evaluating static and dynamic pressure distribution on flat and curved surfaces. Numerous parameters of foot function can be investigated using this system.[26] The EMED-SF® platform produces a maximum pressure picture, which depicts the contact area and pressure distribution of the footprint. Angle of gait can be calculated from this pressure distribution picture, using the EMED-SF® software Geometry program (novel, gmbh, Munich, Germany). The Geometry program refers to the AOG as the foot progression angle or FPA, defined as the angle between the mid axis of the foot and the direction of travel during data collection. As a result, this angle can be used to describe the angle at which the foot contacts the ground.

The purpose of this study was twofold. The first part was to assess the intra and inter rater reliability of measuring AOG using a modified existing validated technique of powdered footprints on paper.[1, 12] The second part consisted of a simultaneous study to compare AOG from powdered footprints and FPA from electronic EMED-SF® footprints to determine whether a relationship existed.

SUBJECTS and METHODS

Part 1

A convenience sample of 6 asymptomatic adults was recruited from a metropolitan private podiatry practice. The sample comprised of three females and three males with a mean (±SD) age of 49.8 ± 14.1 years, a mean body weight of 72 ± 10.6 kg, and a mean height of 1.6 ± 0.1m. Subjects were assessed for criteria which would exclude them from the study, such as a history of neuromuscular disease, lower limb pathology and trauma. The Human Research Ethics Committee at the University of Western Australia approved the study, and subjects provided informed consent before participation.

Methods

Footprint data were obtained using 8m lengths of white paper (80gsm) 92cm wide. The paper was laid out over an elevated walkway 10 meters in length and 1 meter above the floor. A chair was positioned at either end of the paper with a container of talcum powder coloured with blue oxide (1:100) at the base of the chair at one end. The subject was instructed to place their feet in the container and gently shake off any excess powder. The container was removed and the subject instructed to rise from the chair and walk normally to the other end, looking straight ahead, commencing with the right foot and to sit down upon reaching the other end. Following this, artist fixative was sprayed on each footprint, and the trial number recorded on the paper. Once dry, a piece of adhesive transparent contact plastic was placed over each individual footprint before the 8m length of paper was rolled-up. All trials were laminated to facilitate repeated measurements.

To exclude phases of acceleration and deceleration, footprints 3-6 (two left and two right) were identified on each trial, and used to calculate AOG. This process was undertaken under identical conditions, a total of three times, at weekly intervals. Measurements were conducted independently by two observers. In total, 72 footprints per observer were analysed (6 subjects x 4 footprints x 3 trials). The observers used a fine (0.5mm) water-soluble pen, which enabled marks to be erased completely, and did not leave any indentations on the laminated surface. A stainless steel ruler was used to draw lines, and angles were measured with a transparent plastic protractor enabling measurement increments to 0.5 degree.

A transparent grid, made up of parallel lines, was placed over the footprint. The longitudinal border of the grid was aligned with the apex of the hallux and the medial side of the forefoot. To ensure parallel placement of the grid, the distance between the top and bottom margins of the grid and the border of the paper were measured. The grid was used to draw line (A), representing the apex of the hallux. A similar line was drawn (B), at the posterior aspect of the heel, parallel to line (A). The longitudinal border of the grid adjacent to the medial side of the forefoot was marked at either end. The grid was removed and the two points joined to formulate the line of progression (LOP) (Figure 1). The footprint was then subdivided (Figure 2) to produce the foot axis (FX). Angle of gait was derived from the intersection of axis (FX) and the LOP.

Part 2

A separate convenience sample of 11 asymptomatic adults was recruited from the same metropolitan podiatry practice. The sample comprised of six females and five males with a mean (±SD) age of 40.2 ± 13.3 years, a mean body weight of 72.5 ± 15.3 kg, and a mean height of 1.7 ± 0.1 m. A screening protocol identical to part 1 of the study was undertaken, informed consent obtained, and ethical approval given by The Human Research Ethics Committee at the University of Western Australia.

Methods

The force platform images were obtained using an EMED-SF®-4 version 2.1 (novel, gmbh, Munich, Germany) capacitance mat transducer system. The force platform comprised 2736 individual sensors at a density of 4 sensors per centimeter square, with an individual sensor area of 0.25cm^2. The dimensions of the platform were 42 x 41.7 cm with a sensor dimension of 36 x 19 cm, and a sampling frequency of 50Hz. The EMED-SF® force platform was situated flush with the floor surface in the midline of the same walkway used in footprint data collection.

A 2.5 meter sheet of white paper (80gsm) was positioned and secured over the EMED-SF® force platform, with adhesive tape. The subject was allowed to walk over the platform several times to familiarize themselves with the procedure, and a starting position determined to facilitate the two-step method[27-31] of data collection. A container with coloured talcum powder was placed at the starting point and one foot was placed in the container. Excess powder was gently shaken off and the subject commenced walking, looking straight ahead. Data collection on the EMED-SF® was initiated by selecting the auto-trigger function of the system, which enabled simultaneous powdered and electronic footprint acquisition.

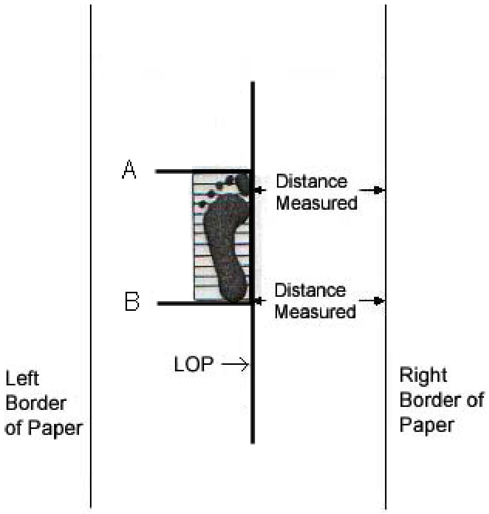

Figure 1. Placement of transparent grid to ensure parallel lines representing the apex of the hallux (A) and posterior border of the heel (B) and equal distances between the vertical border of the grid and the right edge of the paper (LOP = line of progression) (adapted from Taranto et al, 2004).

Figure 2. The length of the footprint was measured from (A) to (B) and divided into thirds (C) and (D), and the proximal third further divided into half (E). The width of the footprint was measured at 17% (E) and 66% (C) of the foot length and midpoints obtained giving the foot axis (FX) (adapted from Taranto et al, 2004).

The subject was asked to create varying positions of in-toe and out-toe, to ensure a wide range of values for measurement. Data were collected from three trials, conducted at 10 minute intervals, on the same day of the left and right feet for each subject. Measurements were undertaken by one observer (MJT). In total, 66 simultaneous powdered footprints and 66 electronic footprints were analysed (11 subjects x 6 footprints).

Data obtained from the EMED-SF® force platform were derived using the Geometry program. The FPA was used as a measure of the AOG. Calculation of FPA was obtained from the maximum pressure picture, with a tangent drawn on the medial and lateral margins of the foot, used to determine forefoot and heel width. Midpoints of the forefoot and rearfoot width determined the foot axis. Intersection of the foot axis and a line representing the direction of travel produced the FPA.

Statistical analysis

All data were entered into Microsoft Excel® for subsequent analysis. Descriptive statistics on AOG and FPA for footprint and EMED-SF® data were calculated. Intra-rater reliability of AOG from powdered footprints was assessed using Pearson's product moment correlation. Inter-rater reliability of AOG measurements from powdered footprints were assessed using a paired t test. Additionally, agreement between raters was assessed using the Bland and Altman statistical model.[32]

Similarly, paired t tests, Pearson's product moment correlation and the Bland and Altman model were used for comparative analysis of simultaneous powdered and electronic EMED-SF® footprint data. For all statistical tests, a probability of $p<0.05$ was used as the criterion for reporting meaningful differences.

RESULTS

Descriptive statistics of AOG from powdered footprints is demonstrated in Table 1. Pearson's product moment correlations between week one and two, and week two and three, was 0.94 and 0.95 respectively for rater 1, and 0.93 and 0.95 for rater 2. The mean difference between rater one and rater two for AOG from powdered footprints was 0.26 (CI: -0.06, 0.57), indicating no significant difference (*t* = -1.63, *P* = 0.108), with a typical error of 0.95. The mean bias and limits of agreement values was 0.26° and 2.62° respectively. This agreement was observed in Figure 3, with most observations occurring within two standard deviations of the mean, however a trend toward positive differences at low values and negative differences at higher values was observed.

Table 1. Descriptive statistics of AOG from powdered footprints

	AOG Mean (degrees)	**AOG SD (degrees)**	**Mean Difference**	**t value**	**P value**	**95% CI**
Rater 1	9.8	3.5	0.26	-1.63	0.108	(-0.06, 0.57)
Rater 2	9.5	3.2				

Table 2. Descriptive statistics of simultaneous footprint and EMED-SF® data

	AOG Mean (degrees)	**AOG SD (degrees)**	**Mean Difference**	**t value**	**P value**	**95% CI**
Footprint AOG	9.0	10.4	0.03	0.09	0.93	(-0.54, 0.59)
EMED-SF® FPA	9.0	10				

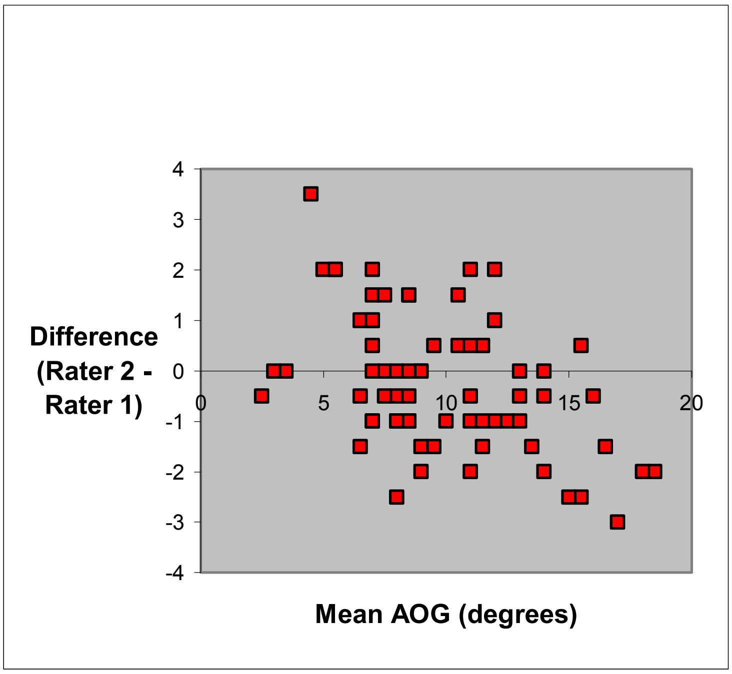

Figure 3. Differences between rater one and rater two for AOG calculation from powdered footprints.

Descriptive statistics for the simultaneous powdered footprint and EMED-SF® are presented in Table 2. The mean difference between AOG from powdered footprints and FPA from EMED-SF® was 0.03 (CI: -0.54, 0.59), indicating no significant difference (*t* = 0.09, *P* = 0.93). A Pearson's product moment correlation of 0.98 (CI: 0.96, 0.99) for AOG using powdered footprints and FPA from the EMED-SF® was observed, illustrated in Figure 4. Assessment of agreement using the Bland and Altman model (Figure 5) confirmed moderate differences between the two methods of measurement. The mean bias and limits of agreement values was 0.03° and 4.52° respectively

DISCUSSION

As previously reported, measurement of gait parameters from powdered footprints is highly reliable, both within and between observers. Intra-observer correlation coefficients were reported to range from 0.92 to 1.00, and inter-rater correlation ranged from 0.94 to 1.00.[12] The present study found similar levels of intra-rater reliability, ranging between 0.93 to 0.95, and inter-rater reliability of 0.93. The typical error (0.95) indicated test retest reliability would provide values to within one degree of each rater, on 95% of occasions.

Previous authors have modified the traditional methodology of calculating AOG[1] under the assumption the line of progression is a dynamic process, and therefore changes are relative to movement of the whole body, rather than a function of each individual limb. The present researchers acknowledged this concept would be of particular importance when assessing abnormal gait patterns, such as those of children or neurologically impaired individuals. This, however, was not considered an issue considering the asymptomatic adult sample population used in the current study.

Investigation into the reliability of geometric analysis of electronic footprints has been reported in the literature, looking both at the same footprint on different occasions and different prints of the same foot. Results demonstrated high intra-rater reliability and consistency in parameters examined,[24] however simultaneous footprints were not investigated.

In a similar study,[23] which compared conventional ink footprints with simultaneously acquired electronic footprints, investigators used a convenience sample of 16 subjects. Findings indicated significant differences in several geometric indexes, with the contact area of the electronic footprint being consistently underestimated. This study used a Musgrave Footprint (Musgrave Systems Ltd, Wrexham, North Wales) foot pressure platform, and obtained a unilateral static footprint. This difference in methodology may explain the level of reliability, which

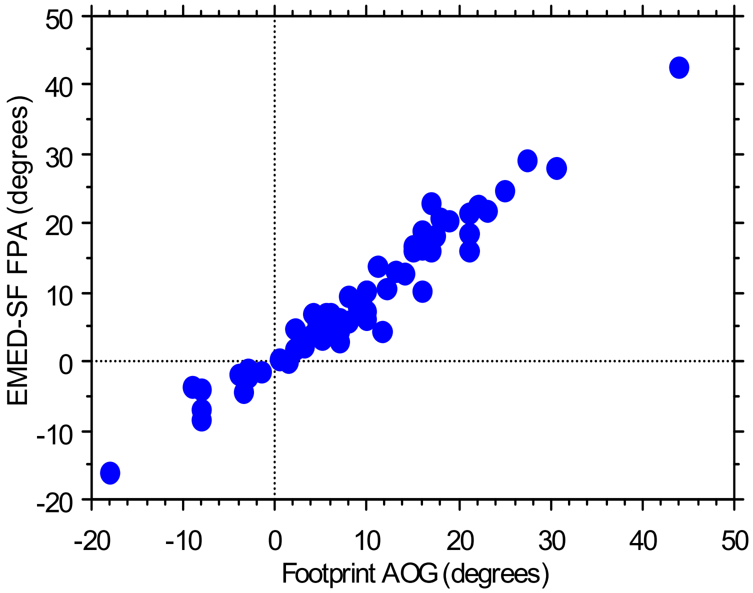

Figure 4. Scattergram between AOG from powdered footprints and FPA from EMED-SF®.

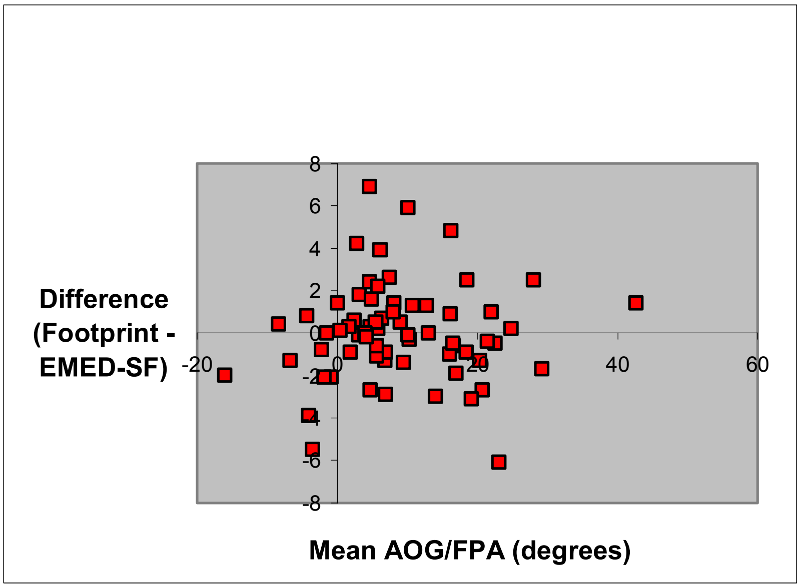

Figure 5. Differences between AOG from powdered footprints and FPA from EMED-SF®.

was higher in the current study whereby dynamic footprints were used. Given AOG is a measure of dynamic function, reliability may be enhanced by measuring it in a dynamic state, as used with the two-step method.

Other factors, which may have contributed to differences in results, were technical specifications of the equipment used in data collection of the electronic footprints. The Musgrave Footprint foot pressure platform had 2048 sensor elements compared to 2736 for the EMED-SF®, representing a 25% increase in sensor elements, perhaps resulting in greater sensitivity to contact area of the foot. The EMED-SF® had 684 cm^2 of active sensor dimension surface area compared to 616 cm^2 for the Musgrave Footprint platform. Similarly, the EMED-SF® had a sensor element area of 0.25 cm^2 compared to 0.3 cm^2 for the Musgrave Footprint pressure platform.

The FPA reported by the EMED-SF® was comparable to the AOG measured from the powdered footprint. As demonstrated, the high reliability and repeatability of the powdered footprint method makes this technique an accessible office based measurement tool, in instances where computer and force platform systems are unavailable.

Several limitations were identified in this study. A larger sample size in both parts of the study would have been desirable, given high correlation coefficients are generally observed in smaller sample sizes. Similarly, the high Pearson's product moment correlation may have been influenced by the large variability in transverse plane foot placement. The authors acknowledge these extreme values may not necessarily be reflective of what is usually observed clinically, however, it was considered important to be able to detect such extremes, particularly in studies investigating transverse plane position of the foot. Assessment of reliability in a larger population would increase external validity. As suggested,[23] size, distribution and sensitivity threshold of force platform sensors are factors which contribute to overall data acquisition and hence analysis. Finally, collection of powdered footprint data for measurement of AOG represented a relatively time consuming technique.

CONCLUSION

Measurement of AOG using powdered footprints demonstrated high reliability. Similar levels of reliability were determined when comparing AOG from powdered footprints and FPA from EMED-SF® pressure profiles in a simultaneous comparison study.

An advantage of the footprint method is low cost in comparison to the EMED-SF® or other laboratory based systems. Additionally, it can be performed as an office based assessment in cases where force platforms may be impractical or expensive. Replication of the methodology used in this study in larger populations would enhance clinical utility of the footprint method as a valid and reliable clinical tool.

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Appendix 2:

Radiographic Investigation of Angular and Linear Measurements including First Metatarsophalangeal Joint Dorsiflexion and Rearfoot to Forefoot Axis Angle

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Keywords: Reliability, Lateral stressed dorsiflexion view, Composite view, First metatarsophalangeal joint dorsiflexion, Forefoot to rearfoot axis angle.

Abstract

This study investigated intra- and inter-rater reliability of several radiographic angular and linear parameters using six subjects. Measurements including first metatarsal protrusion distance, hallux abductus, first intermetatarsal, calcaneal inclination, and lateral intermetatarsal angles were obtained from standard weight-bearing views. Measurement of lateral stressed dorsiflexion of the first MTPJ, and the rearfoot to forefoot axis angle, using a composite view, were obtained. All views were independently measured by two raters, repeated on three separate occasions at weekly intervals.

Intra-rater reliability of radiographic measurements ranged between $R = 0.65$ - 1.00 for lateral stressed dorsiflexion, and between $R = 0.91$ and 0.99 for the rearfoot to forefoot axis angle. Inter-rater reliability of radiographic measurements ranged from $R = 0.82$ - 0.99. Specifically, lateral stressed dorsiflexion showed $R = 0.87$ with a mean difference of –1.47 (CI: -3.42, 0.47), indicating no significant difference ($t = 1.54$, $P = 0.13$). The rearfoot to forefoot axis angle showed $R = 0.92$ with a mean difference of –0.15 (CI: -1.05, 0.74), indicating no significant difference ($t = 0.35$, $P = 0.73$).

The seven angular and linear measurements chosen demonstrated high inter and intra-rater reliability. Results indicated weight-bearing radiographic first MTPJ dorsiflexion using the lateral stressed dorsiflexion view, and measurement of the rearfoot to forefoot axis angle using a composite view could be measured reliably within and between raters.

Introduction

Radiographic investigation of foot disorders is commonplace in podiatric practice. Whether used for assessment, diagnostic or comparative purposes, radiographs provide information, which may influence clinical decision-making. Frequently angular and linear measurements are undertaken in an attempt to quantify the nature of a deformity,[1, 2] and may be used for pre-operative planning of procedures. Subsequent films are also used for comparative purposes. Commonly used radiographic parameters include calcaneal inclination angle (CIA), hallux abductus angle (HAA), first intermetatarsal angle (FIMA), first metatarsal protrusion distance (FMPD) and lateral intermetatarsal angle (LIMA).

Reliability and repeatability of radiographic measurements of the foot has been investigated by many authors, with mixed results. Some studies have shown large variation among raters, suggesting pre- and post-operative angles should not be compared unless measurements have been undertaken by one rater.[3] High intra and inter-rater reliability have previously been demonstrated when measuring angular measurements in hallux valgus deformities.[4] Specifically, Bryant et al[5] reported high intra-rater reliability for CIA (ICC: 0.87), HAA (ICC: 0.96), FIMA (ICC: 0.91), and FMPD (ICC: 0.92). This was consistent with intra-rater reliability findings for HAA (ICC: 0.86), and FIMA (ICC: 0.97) in another study investigating twenty-five pre-operative weight-bearing views.[4] A further study reported a similarly high intra-rater reliability value for CIA (ICC: 0.97) but a much lower value for FIMA (ICC: 0.44).[6]

Despite established reliability parameters of commonly used angular and linear measurements, reliability of less common radiographic measurements has, for obvious reasons, received less attention. Specifically, reliability parameters of radiographic first MTPJ dorsiflexion and measurement of the rearfoot to forefoot axis (RFA) angle have not been established.

Use of a weight-bearing radiograph to measure first MTPJ dorsiflexion has the advantage of allowing an objective and functional weight-bearing depiction of sagittal plane first MTPJ dorsiflexion. This would be of clinical significance when evaluating first MTPJ pathology and treatment outcomes.

Measurement of first MTPJ range of motion has involved static and dynamic methodologies ranging from use of an electromechanical oscillator on cadaver specimens,[7] weight-bearing radiographs,[8-10] goniometry,[11-23] digitisation using video data,[16-24] and, use of an electromagnetic tracking device.[25] However detailed methodology in measuring first MTPJ range of motion in the literature has been shown to be somewhat limited with regards to a standardized technique to quantify and reliably reproduce values given for normal range of motion.[10, 11] Variability in such methodologies highlighted the need for a consistent method utilising reproducible landmarks and good reference lines to measure first MTPJ range of motion. This is of particular importance when rating scales of radiographic deformities are consulted to assess foot function, operative intervention and clinical outcomes.

Reliability of the lateral stressed dorsiflexion (LAT SD) view of the first MTPJ methodology has received little attention in the literature. Joseph[9] was the first author to report on significance of radiographic measurement of first MTPJ dorsiflexion using a weight-bearing lateral radiograph, however made no mention of reliability parameters. A limitation of his study was the exclusion of women, a group largely afflicted with deformities affecting the first MTPJ. Joseph[9] identified a source of error in his study was inconsistency in selection of axes between radiographs.

Some years after the study by Joseph[9], a further investigation by Buell et al[10] was undertaken to establish normal values and test the methodology for obtaining first MTPJ range of motion. These authors compared clinical measurement of first MTPJ range of motion to that found radiographically, and reported a high correlation for active and passive dorsiflexion. This correlation was similar to that found by Joseph[9]. Limitations of the study by Buell et al[10] were they failed to include subject demographics, incomplete details of the methodology and instrumentation used, and inadequate statistical analysis was performed. The results were reported as averages only, reliability parameters were not established, there was mention of further data evaluation, however this was not explained or presented, and there did not appear to be any use of further statistical analyses such as correlations.

Similarly, reliability of the composite (COMP) view[26] has not been established. The COMP view consists of a double exposure dorsoplantar radiograph that requires the plantar aspect of the foot to remain in contact with the film whilst both exposures are taken, as described in detail in the methodology section of this paper. Although the composite view has not been used extensively in research or clinical practice, it presents the advantage of viewing the entire skeletal anatomy of the foot. This enables the privilege of being able to visualise and bisect the most posterior border of the calcaneus, normally obscured by the leg, in a standard dorsoplantar view of the foot. In doing so, radiographic measurements relating to the rearfoot to forefoot relationship are possible, and of particular interest when investigating degrees of transverse plane angulation of the forefoot on the rearfoot.

Use of the COMP view to radiographically determine the RFA, was first described in a study by Freychat et al,[27] whereby relevance of the RFA angle was based on the findings by Bojsen-Moeller[28] that the forefoot and rearfoot may act independently, and foot position is influenced by mobility around the midtarsal joint. In the study by Freycaht et al,[27] the RFA obtained from the COMP radiograph was transferred onto a footprint generated from a force platform. Mean values of 8.4° and 0.7° were reported for the RFA angle from static and dynamic situations respectively. However, reliability parameters for the RFA angle were not established by Freychat et al,[27] and to the authors knowledge, there have not been any investigations since to do so. Additionally, the lack of comparative studies and establishment of normal values identified a void in the existing literature.

Rationale for the methodology involving the establishment of axes from radiographs rather than from clinical examination adopted by Freychat et al[27] was to reduce potential sources of error such as location of anatomical landmarks and soft tissue influence. Although skin movement has been reported to be a potential source of error in measurement of first MTPJ range of motion[11] and rearfoot measurements,[29] Umberger et al[30] found only very small differences in measurements of sensors between skin and skeletal application in a cadaver study using an electromagnetic tracking device to measure static sagittal plane orientation of the first MTPJ, which in another study was correlated to first MTPJ range of motion during gait.[25] However, Umberger et al[30] acknowledged that the effect of underlying muscles and tendons on skin displacement would potentially be greater in a biological specimen.

An element of controversy was identified in the literature regarding interpretation of radiographic measurements due to sources of error such as choosing landmarks, constructing lines,[31] reading of the measurement tool, over-exposure of the x-ray,[32] foot positioning, relationship of the foot to the central ray and the cassette,[33, 34] and arch height in relation to declination of the metatarsals.[35] Additionally, magnification and distortion of foot bones has also been recognized.[36, 37]

Perry et al[38] stated radiographs may be misleading because they provide two-dimensional information of a three-dimensional structure. Comparing radiographic measurements to actual bone measurements following Chevron osteotomies both in vitro and in vivo, they noted radiographic changes in length were greater than actual bone changes, concluding radiographs should not be used to detect subtle differences. Schneider et al[31] evaluated measurement accuracy of five different methods of defining the longitudinal axis of the first metatarsal to assess intra- and inter-rater reliability, believing the centre of the metatarsal head was least biased by post-operative effects when compared to measurements using the metatarsal shaft as a reference for the first metatarsal axis.

Although reliable and repeatable, comparison between radiographic studies becomes difficult because of the adoption of different methodologies. This has particular importance with regard to the selection of reference points in drawing reliable axes. Representing the American Orthopaedic Foot and Ankle Society (AOFAS), Coughlin et al[39] made the following recommendations for radiographic investigation of angular measurements: use of standardised radiographs; use of the same measurement tool or equipment for all radiographs; the need for specific, easy to define reference points; and, use of a protractor rather than a goniometer to measure angles.

The purpose of this study was to assess the intra- and inter-rater reliability of seven radiographic angular and linear measurement variables, with specific interest on first MTPJ dorsiflexion and the rearfoot to forefoot axis (RFA) angle. In order to confidently measure lateral stressed dorsiflexion of the first MTPJ and the RFA angle respectively, reliability parameters were established to help fill the existing gap in the literature.

Methods

A convenience sample of 6 adults presenting with hallux limitus or hallux valgus was recruited from a metropolitan private podiatry practice. Subjects were assessed for criteria, which would exclude them from the study. These included a history of lower limb surgery, trauma, gait abnormalities, neurological disorders or any systemic disease. The Human Research Ethics Committee at the University of Western Australia approved the study, and subjects provided informed consent before participation.

Each subject had a series of bilateral weight-bearing radiographs taken, and coded alpha-numerically. Radiographic views included: dorsoplantar (DP), lateral (LAT), lateral stressed dorsiflexion of the first MTPJ (LAT SD) and composite (COMP) views. Following the recommendation of the AOFAS,[39] three radiographers from the same clinic followed a standardized methodology using a single x-ray unit and standard values for focal distance, central ray, and exposure. The radiographers had undertaken a period of instruction with the researcher to orientate themselves with the procedural protocol and specific views required.

Radiographic Process

The LAT SD view[9, 10] of the first MTPJ was taken as per a standard lateral view, however the central ray was directed at the first MTPJ. The knee was flexed 40° and the heel raised off the ground to the point where the first MTPJ was in maximum dorsiflexion, without any obvious frontal or transverse plane movement.

For the COMP view,[26] a double exposure was required. The subject was positioned as per the DP view. The first exposure involved positioning the patient in an upright posture, with the foot to be imaged extended forward and the plantar aspect of the foot in contact with the film (Figure 1a). The central ray was centered over the ankle and the first exposure taken (Figure 1b). The subject was then required to keep the foot to be imaged in the same position, but step forward with the opposite leg. The x-ray tube was not displaced and as a result the central ray passed through the posterior aspect of the ankle joint and the second exposure taken (Figure 1c). Both exposures were set at 62KV, 125mA and 0.05sec.

For the DP view,[40] the subject stood on the film, which was flat on the orthoposer. As the subject's angle and base of gait were considered in this view[33], each foot was exposed separately using a lead shield to cover the other half of the x-ray film.

For the LAT view,[40] the x-ray cassette was positioned vertically in the lead lined orthoposer, with one foot placed on each side of the film. The medial aspect of the foot to be radiographed was touching the film.

Radiographic Measurement

For each subject, seven dependant variables were obtained for left and right feet (14 per subject) consisting of HAA, FIMA, FMPD, LAT SD of the first MTPJ, RFA angle, CIA and LIMA.

A sheet of clear acetate was firmly secured over each radiograph so there was no movement of the sheet and it was not necessary to mark the actual radiograph. Using a fine (0.5mm) water-soluble pen, angular and linear measurements were made on the radiographs and recorded. This process was independently repeated three times by two raters (MT and JT), at one-week intervals, with raters blinded to previous results. After each measurement session, the acetate sheets were removed, wiped clean of any marks and radiographs were re-measured at random. A total of 504 measurements were undertaken (6 subjects x 7 angular measurements x 2 feet x 2 raters x 3 measurement sessions). Data recorded was tested for intra and inter-rater reliability of measurement, and used in the analysis.

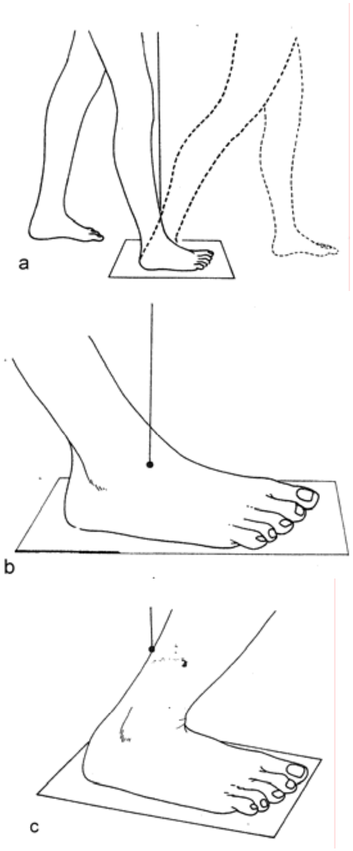

FIGURE 1 Radiographic technique for COMP view showing position of subject and central ray (adapted from Montagne et al[26], 1981).

Radiographic measurement of first MTPJ dorsiflexion[9, 10] was obtained using the LAT SD view. The dorsal and plantar cortices of the proximal and distal thirds of the first metatarsal shaft were identified, and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by the intersection of these two lines represented the amount of first MTPJ dorsiflexion (Figure 2). Normal values for first MTPJ dorsiflexion have been reported as being at least 65°,[16, 41] although normal values from radiographs have been reported as ranging from 40°-100° in Joseph's study,[9] and more specifically, 82° in that by Buell et al.[10]

Radiographic measurement of the RFA[27] was obtained using the COMP view. The posterior sclerotic margin of the calcaneus was bisected to obtain the point representing the rear extremity of the calcaneus. The most medial and lateral margins of the calcaneocuboid joint were identified and bisected, to obtain the point representing the calcaneocuboid joint. These two points were connected and extended distally, representing the rearfoot axis. The second and third metatarsals were each bisected at the level of the anatomical neck to obtain two points. The distance between these two points was measured and bisected. The resultant point was connected to the calcaneocuboid joint, to obtain the forefoot axis. The angle between the intersection of the rearfoot axis and the forefoot axis was termed the RFA angle (Figure 3). Normal values for RFA were not reported in the literature**.**

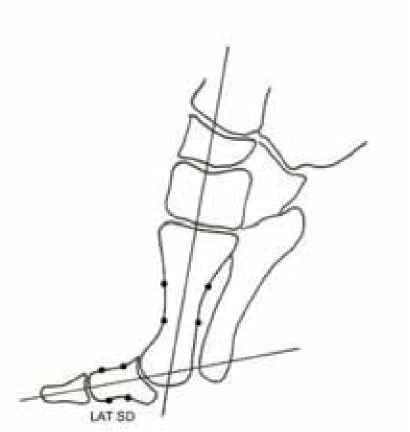

FIGURE 2 Calculation of LAT SD from weight-bearing LAT SD view.

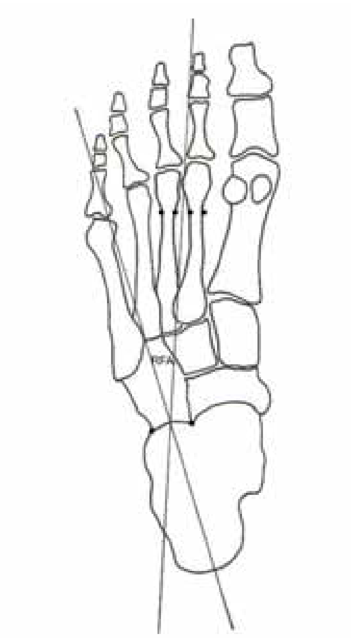

FIGURE 3 Calculation of RFA angle from weight-bearing composite view.

The LAT view was used to obtain the CIA and LIMA (Figure 4). For the CIA,[40] a line was drawn representing the weight-bearing surface of the foot. A second line was drawn along the calcaneal inclination axis. According to Gamble and Yale,[40] CIA was classified as low 0°-10°, medium 10°-20°, or high 20°-30°.

The literature identified several methods[42-46] of calculating elevation of the first metatarsal in relation to the second. Using weight-bearing lateral radiographs, Horton et al[47] measured the difference of the vertical distance of the first metatarsal above the second at the level of the distal metaphyseal flare. However, vertical distance between the first and second metatarsal does not imply elevation, given the normal anatomical elevation of the first metatarsal.[47] Rather, whether or not the first metatarsals were parallel was of importance, and although these authors did measure the difference between declination of the first and second metatarsals, this was not the value used to indicate elevation.

Christman et al[44] used a computer assisted device to measure the effect of x-ray tube angulation and central ray direction on the position of the first and second metatarsals from a weight-bearing lateral radiograph of a foot phantom. However, reliability parameters were not reported.

Schuberth et al[42] compared the dorsal cortices of the first and second metatarsals in relation to the weight-bearing surface, and termed the resultant angle the sagittal intermetatarsal angle. Although this methodology took into account the sagittal plane divergence of the two metatarsals, there was no evidence of established measurement reliability. Bryant et al[45] used a similar methodology to that of Schuberth et al,[42] without comparison to the weight-bearing surface. The method of Bryant et al[45] for LIMA was used in the present study because of the established intra-rater reliability (ICC: 0.97).

The central region of the dorsal cortex of the first and second metatarsal shafts were marked and the resultant angle formed by the intersection of these two lines measured (Figure 4). Bryant et al[45] reported normal mean values for LIMA as being 1.02°.

The DP view was used to obtain the HAA, FIMA and FMPD. For the HAA,[48] the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified, and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by these intersecting lines was measured. Most authors agreed a HAA value of less than 15° was considered normal,[40, 49-51] however Hardy and Clapham[52] reported a range of 0°-20° as normal. This was supported by Antrobus[53] and Houghton and Dickson[54] who found an average of 18.7° and 16.7° for HAA in their normal subjects respectively.

For the FIMA,[48] the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft were identified, and bisected. This was repeated for the second metatarsal. The angle formed by these intersecting lines was measured. Normal values for FIMA were reported as being between 8°-14°.[48]

Literature identified several methods of calculating FMPD.[46, 55, 56] Hardy and Clapham[52] measured the distance between the compass arcs of the first and second metatarsal heads from a reference point formed by the intersection of the mid-axis of the second metatarsal and a transverse tarsal line. This methodology was later used by Smith et al.[55] LaPorta et al[57] described a similar method but used the intersection of the first intermetatarsal angle with the tarsal line as the reference for the compass arm rather than the bisection of the second metatarsal.

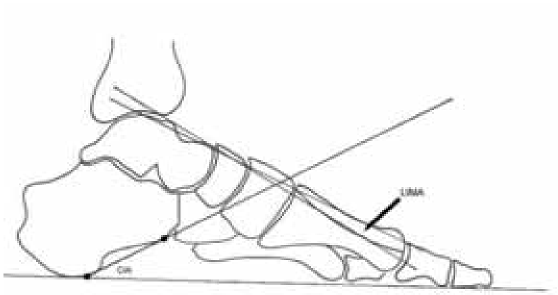

FIGURE 4 Calculation of CIA and LIMA from weight-bearing LAT view.

Duke et al[56] modified the method of LaPorta et al,[57] excluding the transverse tarsal line as the point for the compass arm, and instead used the intersection of the intermetatarsal angle. The methodology used by Duke et al[56] was used in the present study because it increased consistency and reduced the margin for measurement error by using one less reference point. Calculation of FMPD was undertaken with a compass containing a 0.5mm water-soluble felt tip marker as follows: the point of the proximal arm was positioned at the intersection of the FIMA, and a line drawn with the distal arm at the level of the central articulating surface of the first metatarsal head, and extended laterally to be in line with the second metatarsal. Keeping the proximal arm of the compass stationary, the distal arm was then positioned at the central articulating surface of the second metatarsal head, and a line drawn and extended medially to be in line with the first metatarsal. The distance between these two lines was measured, and represented the FMPD, measured in millimeters (mm). A positive value denoted the first metatarsal was longer than the second. Conversely, a negative value indicated the first metatarsal was shorter than the second (Figure 5) Landers[48] suggested normal FMPD was –2 mm, however LaPorta et al[57] reported normal values of ±2 mm.

Radiographic measurement reliability

Measurement data were transferred into Microsoft Excel®, for descriptive statistical reporting and subsequent analysis. An alpha level of $P < 0.05$ was selected as statistically significant. All dependent variables were examined using graphical techniques and random effects models to describe variability between raters for the seven dependent variables. Intra-rater reliability of the dependent variables was assessed by Pearson’s product moment correlation and random effects ANOVA. Inter-rater reliability of the dependent variables was assessed by Pearson’s product moment correlation. Paired t tests and confidence intervals were calculated to detect differences in the means of each dependent variable between raters.

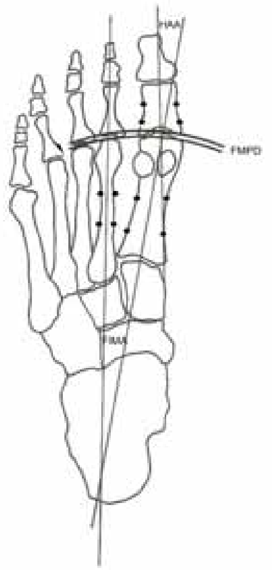

FIGURE 5 Calculation of HAA, FIMA and FMPD from weight-bearing DP view.

Results

The sample comprised of two males and four females with a mean (±SD) age of 58 (±14) years, a mean body weight of 62.2 (±11.8) kg, and a mean height of 1.57 (±0.11) m. Descriptive statistics obtained from the seven dependent variables are presented in Table 1.

Intra-rater reliability

Intra-rater reliability for the dependent variables for each rater are presented in Table 2. Intra-rater reliability of the group of radiographic measurements as assessed by Pearson's product moment correlation ranged between 0.83 – 0.99 for rater 1, and 0.65 – 1 for rater 2, between trials 1 and 2. Between trials 2 and 3, a Pearson's product moment correlation of 0.65 – 1 and 0.72 - 1 was observed for rater 1 and rater 2 respectively. Specifically, intra-rater reliability of the lateral stressed dorsiflexion view of the first MTPJ was higher for rater 2 (*R* = 0.96 and 0.91), than for rater 1 (*R* = 0.86 and 0.90), between trials 1 and 2, and, 2 and 3 respectively. Measurement of the RFA angle using the composite view showed similar levels of intra-rater reliability. Between trials 1 and 2, and trials 2 and 3 respectively, both raters showed similar levels (rater 1: *R* = 0.95 and 0.99; rater 2: *R* = 0.96 and 0.91).

Variability due to different subjects and the within subject variability for both raters was examined using random effects ANOVA models as presented in Table 3. The percentage due to each rater differed for the dependent variables, however the percentage remained consistent for the two raters. The dependent variables LAT SD, FIMA, and LIMA all had higher within subject variability (high rater error) than the other variables for both raters.

Inter-rater reliability

Inter-rater reliability for the dependent variables are presented in Table 4, highlighting Pearson's product moment correlations, confidence intervals and significant paired t tests. Inter-rater reliability of radiographic measurements as a group was high, ranging from R = 0.82 - 0.99. Specifically, inter-rater reliability of the lateral stressed dorsiflexion view of the first MTPJ was R = 0.87 with a mean difference of –1.47 (CI: -3.42, 0.47), indicating no significant difference (*t* = 1.54, *P* = 0.13). The RFA angle showed an inter-rater reliability of R = 0.92 with a mean difference of –0.15 (CI: -1.05, 0.74), indicating no significant difference (*t* = 0.35, *P* = 0.73).

TABLE 1 Mean and standard deviation of dependent variables for rater 1 and rater 2

Dependent Variable	Mean (SD) (degrees) Rater 1	Rater 2
CIA	26 (3.7)	25.1 (4.1)
HAA	16.5 (7.6)	17.7 (9)
FIMA	11.5 (2.5)	11.1 (2.8)
FMPD	5.2 (4.3)	5.2 (4.3)
LAT SD	64.1 (11.2)	62.6 (11)
RFA angle	16.8 (6.7)	16.7 (6.5)
LIMA	4.5 (2.4)	4.5 (2.4)

CIA = calcaneal inclination angle
HAA = hallux abductus angle
FIMA = first intermetatarsal angle
FMPD = first metatarsal protrusion distance
LAT SD = lateral stressed dorsiflexion of first MTPJ
RFA angle = rearfoot to forefoot axis angle
LIMA = lateral intermetatarsal angle

TABLE 2 Pearson's product moment correlations of dependent variables between weeks 1 and 2, and weeks 2 and 3, for intra-rater reliability of each rater

Dependent Variable	Rater 1		Rater 2	
	Week 1/2	Week 2/3	Week 1/2	Week 2/3
CIA	0.99	1.00	0.98	0.80
HAA	0.90	0.97	0.97	0.96
FIMA	0.89	0.94	0.65	0.72
FMPD	0.98	0.99	1.00	1.00
LAT SD	0.86	0.90	0.96	0.91
RFA angle	0.95	0.99	0.90	0.84
LIMA	0.83	0.65	0.74	0.79

CIA = calcaneal inclination angle
HAA = hallux abductus angle
FIMA = first intermetatarsal angle
FMPD = first metatarsal protrusion distance
LAT SD = lateral stressed dorsiflexion of first MTPJ
RFA angle = rearfoot to forefoot axis angle
LIMA = lateral intermetatarsal angle

Analysis of paired t tests showed no statistically significant difference between raters for LAT SD, RFA angle, FIMA, LIMA and FMPD. The only dependent variable that reported a statistically significant difference (*t* = -3.32, *P* = 0.002) between the two raters was CIA with rater 2 scoring on average 0.94 lower than rater 1 (95%CI: -1.52, -0.37). The variable HAA had borderline statistical significance (*t* = -1.89, *P* = 0.07) with a mean of 1.21 (95% CI: -0.09, 2.51), giving some indication of higher readings being recorded by rater 1 than

TABLE 3 Variability within each rater using random effects ANOVA models

Dependent Variable	Rater 1			Rater 2		
	Subject variation estimate	Within Subject variation estimate	Percentage due to rater	Subject variation estimate	Within Subject variation estimate	Percentage due to rater
CIA	14.63	0.14	0.94	14.59	2.74	15.79
HAA	54.41	6.03	9.98	81.08	4.53	5.29
FIMA	6.03	0.63	9.39	6.08	2.24	26.9
FMPD	19.91	0.08	0.38	19.86	0.03	0.17
LAT SD	113.15	18.32	13.93	114.9	11.87	9.36
RFA angle	45.43	1.58	3.35	40.16	4.26	9.6
LIMA	4.14	1.67	28.7	4.65	1.4	23.06

CIA = calcaneal inclination angle
HAA = hallux abductus angle
FIMA = first intermetatarsal angle
FMPD = first metatarsal protrusion distance
LAT SD = lateral stressed dorsiflexion of first MTPJ
RFA angle = rearfoot to forefoot axis angle
LIMA = lateral intermetatarsal angle

TABLE 4 Results of paired t tests and confidence intervals for dependent variables

Dependent Variable	Mean Difference (Rater 2- Rater 1)	95% Confidence Interval	t-Value	ICC
CIA	-0.94	(-1.52, -0.37)	-3.33*	0.91
HAA	1.21	(-0.09, 2.51)	-1.89	0.91
FIMA	-0.33	(-1.01, 0.34)	-1.01	0.73
FMPD	-0.03	(-0.11, 0.05)	0.70	0.99
LAT SD	-1.47	(-3.42, 0.47)	1.54	0.87
RFA angle	-0.15	(-1.05, 0.74)	-0.35	0.92
LIMA	-0.03	(-0.51, 0.45)	0.03	0.82

* $P < 0.05$
CIA = calcaneal inclination angle
HAA = hallux abductus angle
FIMA = first intermetatarsal angle
FMPD = first metatarsal protrusion distance
LAT SD = lateral stressed dorsiflexion of first MTPJ
RFA angle = rearfoot to forefoot axis angle
LIMA = lateral intermetatarsal angle

rater 2 for this variable. Overall, variability between raters was minimal.

Observation of graphical plots for LAT SD and RFA angle for rater one and rater two showed the majority of points fell within two standard deviations of the mean, which indicated good agreement between the two raters.

Discussion

Intra-rater and inter-rater reliability was calculated for CIA, HAA, FIMA, FMPD, LAT SD, RFA angle, and LIMA. Despite a limitation of the current study being the small sample size, values for intra and inter-rater reliability were consistent with findings in the literature, which employed similar and larger populations. The following discussion compares results obtained from this study with those found in the literature. Results are presented in parentheses, the first value indicating that obtained from rater 1 and the second from rater 2. For the purpose of discussion, the average of the Pearson's product moment correlation coefficient obtained from weeks one and two, and weeks two and three, is used.

This study showed similar reliability parameters for FIMA (R: 0.92, 0.69) HAA (R: 0.94, 0.97) FMPD (R: 0.99, 1.00) and CIA (R: 1.0, 0.89) found in a previous investigation measuring various weight-bearing angular and linear measurements, from six DP and six LAT radiographic views on three separate occasions (ICC: FIMA: 0.91; HAA: 0.96; FMPD: 0.92; CIA: 0.87).[5] This was also consistent with HAA and FIMA reliability values of Coughlin and Freund (ICC: HAA: 0.86; FIMA: 0.97),[4] and CIA reliability values of Cavanagh et al,[6] although they observed a lower value for FIMA (ICC: CIA:0.97; FIMA: 0.44).[6]

In regard to assessment of variability within raters, a high level of agreement existed. Examination of graphical plots demonstrated minimal differences between raters for LAT SD, indicating this variable can be measured reliably. Further study investigating the comparability between first MTPJ range of motion from radiographic LAT SD and clinical goniometry measurements would be needed to confidently use the LAT SD measurement to quantify first MTPJ dorsiflexion in the clinical setting and in perioperative analysis. Despite the attempt made by Buell et al[10] to do this, limitations identified in their study resulted in questionable conclusions.

No significant difference was found between raters for the RFA angle, however given there was more variation for larger values than smaller values, a log transformation was undertaken for further analysis. This showed the intraclass correlation coefficient to be only slightly lower (ICC: 0.92), indicating RFA angle can be used reliably between raters. Furthermore, RFA angle may be useful in further studies relating to angle of gait, or abduction/adduction of the foot as a whole, as opposed to abduction/adduction of the forefoot on the rearfoot. In this way, the RFA angle could be used to differentiate between intrinsic structural transverse plane abnormalities of the foot, such as metatarsus adductus, and extrinsic compensatory mechanisms.

The CIA, showed a significant difference with lower scores observed for rater 2 than rater 1. The only other dependent variable to demonstrate a borderline statistically significant difference was HAA, with rater 1, on average, observing higher values than rater 2, however the differences did not appear to be dependent on measurement size. The dependent variables CIA, HAA, FMPD and RFA angle had lower within subject variability, hence lower rater error, than FIMA, LIMA and LAT SD.

Subjects in this study presented with a deformity of the first MTPJ, therefore values obtained from the dependent variables were expected to vary from normal reference ranges observed in the literature. The following discussion presents the mean values of each dependent variable with scores presented in parentheses for rater 1 and 2 respectively.

Both raters reported mean values of CIA (26.0°, 25.1°) consistent with the classification of a high CIA.[40] Each rater reported HAA values above normal (16.5°, 17.7°) if the threshold advocated by Piggott et al[50] was accepted, although these values would be considered normal by other authors.[52-54] Despite the presence of hallux valgus in this study, values reported for FIMA (11.5°, 11.1°) were consistent with the normal range of 8°-14°.[48] Higher that normal values[48, 57] were reported for FMPD (5.2°, 5.2°) perhaps indicating some role of metatarsal length in first MTPJ pathology. Values for LAT SD were normal (64.1°, 62.6°) if compared to those obtained by Joseph,[9] but much less than normal if the observations by Buell et al[10] were considered. Normal values for RFA angle were not reported in the literature, and the values obtained in the present study (16.8°, 16.7°) should not be considered normal because of the sample used. Values found for LIMA (4.5°, 4.5°) were above normal values reported by Bryant et al.[45]

Radiographic measurements are subject to many sources of error, which can be minimized by standardizing the radiographic equipment, radiographic technique, and technique of measurement, as undertaken in this study. This is of particular importance when comparisons between subjects are made, or measurements are undertaken before and after clinical or surgical intervention. In the present study, removal of the clear acetate sheet following measurements avoided the problems associated with incomplete removal of lines. The experience of the raters was another potential source of error. It has been thought intra-rater reliability improves with experience,[58] although some studies reported no improvement in reliability with increasing experience.[4, 59, 60]

Conclusion

Selected measurement parameters from weight-bearing foot radiographs were assessed and found to exhibit high intra- and inter-rater reliability, consistent with findings observed in the literature. Specifically, the method of obtaining the lateral stressed dorsiflexion of the first MTPJ was shown to be reliable. Similar reliability was observed for the rearfoot to forefoot axis angle obtained from the composite view of the foot, providing a unique method of assessing the radiographic forefoot to rearfoot relationship in the transverse plane. Further investigation should attempt to compare radiographic and clinical measurements of first MTPJ dorsiflexion, and if possible, the rearfoot to forefoot relationship, such that their relevance to clinical examination can be established.

Acknowledgments

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Appendix 3:

Analysis of dynamic angle of gait characteristics in subjects with Bunions.

Julie Taranto, Dr Kevin Singer and Dr Alan Bryant

Subject Information

Bunion deformities are among the most common conditions that can affect people's feet. There are many factors that can lead to the development of bunions including the length of particular bones in the foot, and the angles they form and how a person walks. This investigation will look at measuring certain angles formed by the bones in the foot using x-rays and footprints obtained using coloured talcum powder and paper.

You have been invited to participate in this study, as your foot demonstrates the condition of interest (or it may represent a comparison foot type known as a control). Involvement in this study will involve five x-ray views taken of the left and right feet (10 in total) at a designated radiology clinic, (approximately 20 minutes plus travel time) at a time convenient to you. Footprints using coloured talcum powder will be obtained on a designated day and time stipulated by Julie Taranto. There will be no anticipated discomfort, inconvenience or further time required to participate in this study. From these x-rays and footprints, data such as bone length, position and angle of walking will be derived and assessed. On completion of the study, the data will be stored in a secure location at the Centre of Musculoskeletal Studies at the University of Western Australia for a period of 7 years. If there are any questions concerning the proposed research, Julie Taranto can be contacted on 9250 1676 or 0417 821 478 to offer assistance.

Your participation in this study is entirely voluntary. Furthermore, your participation does not pose any foreseeable short or long-term side effects or hazards. Non-participation or withdrawal from the study will not affect subsequent podiatry treatment.

Consent

I ___________________________________ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason and without prejudice. I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required by law. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research. I agree that research data gathered for the study may be published provided my name or other identifying information is not used.

Participant *(Print Name and Sign)* *Date*

The Human Research Ethics Committee at the University of Western Australia requires that all participants are informed that, if they have any complaint regarding the manner, in which a research project is conducted, it may be given to the researcher or, alternatively to the Secretary, Human Research Ethics Committee, Registrar's Office, University of Western Australia, 35 Stirling Highway,Crawley, WA 6009 (Telephone number 9380 3703). All study participants will be provided with a copy of the Information Sheet and Consent Form for their personal records.

Appendix 4

Angle of Gait Data Recording Sheet

Footprint No.	**Angle of Gait from Footprints (degrees)**
L1	
R1	
L2	
R2	

Observer: ________
Subject ID:________

Footprint No.	**Angle of Gait from Footprints (degrees)**
L1	
R1	
L2	
R2	

Observer: ________
Subject ID:________

Footprint No.	**Angle of Gait from Footprints (degrees)**
L1	
R1	
L2	
R2	

Observer: ________
Subject ID:________

Appendix 5

Radiographic Measurements Data Recording Sheet

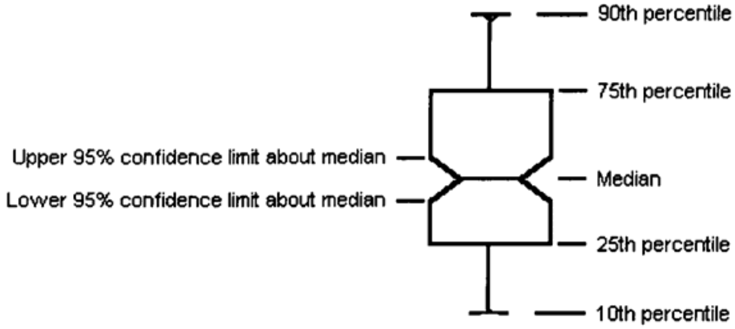
VIEW	**Radiographic Measurements**		
		L	**R**
LAT	CIA (degrees)		
	LIMA (degrees)		
DP	HAA (degrees)		
	FIMA (degrees)		
	FMPD (mm)		
LAT SD	LAT SD (degrees)		
COMP	RFA angle (degrees)		
	Observer: ________ Subject ID:________		

VIEW	**Radiographic Measurements**		
		L	**R**
LAT	CIA (degrees)		
	LIMA (degrees)		
DP	HAA (degrees)		
	FIMA (degrees)		
	FMPD (mm)		
LAT SD	LAT SD (degrees)		
COMP	RFA angle (degrees)		
	Observer: ________ Subject ID:________		

Appendix 6

Notched Box Plot

(StatView. *StatView Reference*. 3rd ed: SAS Institute Incorporated; 1999)



Appendix 7

Summary of Logistic Regression Analyses

Logistic Regression 1:

In the assessment below, HAA was excluded. The logistic regression reported that when all other dependent variables were considered, 91.67% of HV subjects were allocated to the HV group, and all control subjects were allocated to the control group. Overall, there was a 96.05% accuracy that subjects would be allocated to the correct group.

HV = 0, Control = 1

Logistic Summary Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

Count	76
# Missing	0
# Response Levels	2
# Fit Parameters	8
Log Likelihood	-13.674
Intercept Log Likelihood	-52.574
R Squared	.740

Logistic Whole Model Fit Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	DF	Chi-Square	P-Value
Pearson	68	85.332	.0761
Deviance	68	27.348	>.9999
Likelihood Ratio	7	77.800	<.0001

Logistic Model Coefficients Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	Coef	Std. Error	Coef/SE	Chi-Square	P-Value	R	Exp(Coef)	95% Lower	95% Upper
CONTROL: constant	-11.084	8.296	-1.336	1.785	.1815	0.000	1.536E-5	1.331E-12	177.284
CIA	.108	.144	.753	.566	.4517	0.000	1.115	.840	1.478
LIMA	.361	.320	1.127	1.270	.2598	0.000	1.434	.766	2.685
FMPD	-.061	.183	-.336	.113	.7372	0.000	.940	.657	1.346
RFA	.028	.062	.450	.202	.6530	0.000	1.028	.911	1.161
AOG	-.224	.133	-1.688	2.851	.0913	-.090	.799	.616	1.037
LAT SD	.274	.086	3.187	10.156	.0014	.279	1.315	1.111	1.557
FIMA	-.941	.355	-2.652	7.033	.0080	-.219	.390	.195	.782

Logistic Likelihood Ratio Tests Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	DF	Chi-Square	P-Value
CIA	1	.627	.4286
LIMA	1	1.494	.2216
FMPD	1	.112	.7376
RFA	1	.204	.6512
AOG	1	3.059	.0803
LAT SD	1	30.235	<.0001
FIMA	1	16.223	<.0001

Logistic Classification Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	Predicted HV	Predicted CONTROL	Percent Correct
Observed HV	33	3	91.67%
Observed CONTROL	0	40	100.00%
Overall			96.05%

Logistic Regression 2:

In the assessment below, HAA, LAT SD, and FIMA were excluded. The logistic regression reported that when all other dependent variables were considered, 55.56% of HV subjects were allocated to the HV group, and 65% of control subjects were allocated to the control group. Overall, there was a 60.53% accuracy that subjects would be allocated to the correct group. These results indicate that HAA, LAT SD, and FIMA, were the best predictors of group allocation.

HV = 0, Control = 1

Logistic Summary Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

Count	76
# Missing	0
# Response Levels	2
# Fit Parameters	6
Log Likelihood	-48.449
Intercept Log Likelihood	-52.574
R Squared	.078

Logistic Whole Model Fit Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	DF	Chi-Square	P-Value
Pearson	70	75.035	.3185
Deviance	70	96.899	.0184
Likelihood Ratio	5	8.249	.1430

Logistic Model Coefficients Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	Coef	Std. Error	Coef/SE	Chi-Square	P-Value	R	Exp(Coef)	95% Lower	95% Upper
CONTROL: constant	-2.160	1.621	-1.332	1.775	.1828	0.000	.115	.005	2.767
CIA	.093	.058	1.607	2.581	.1081	.074	1.097	.980	1.229
LIMA	.091	.107	.846	.716	.3974	0.000	1.095	.888	1.351
FMPD	-.070	.081	-.862	.742	.3889	0.000	.933	.796	1.093
RFA	.053	.037	1.441	2.077	.1495	.027	1.055	.981	1.134
AOG	-.104	.053	-1.978	3.911	.0480	-.135	.901	.813	.999

Logistic Likelihood Ratio Tests Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	DF	Chi-Square	P-Value
CIA	1	2.784	.0952
LIMA	1	.724	.3950
FMPD	1	.757	.3841
RFA	1	2.154	.1422
AOG	1	4.545	.0330

Logistic Classification Table for GROUP
Row exclusion: HV FEET V CONTROL FEET TO 1.svd

	Predicted HV	Predicted CONTROL	Percent Correct
Observed HV	20	16	55.56%
Observed CONTROL	14	26	65.00%
Overall			60.53%

Appendix 8

Hallux Valgus Raw Data

ID	CIA (L)	CIA (R)	LIMA (L)	LIMA (R)	HAA (L)	HAA (R)	FIMA (L)	FIMA (R)	FMPD (L)	FMPD (R)	LAT SD (L)	LAT SD (R)	RFA (L)	RFA (R)
1HV	31.500	33.000	1.500	2.500	27.500	8.000	16.000	11.000	4.000	0.000	66.000	68.500	7.500	10.500
2HV	25.500	24.500	3.500	2.000	21.000	16.000	12.000	10.000	1.000	1.000	61.000	56.500	21.000	18.000
3HV	23.500	24.000	5.000	3.500	21.000	15.000	6.500	6.500	5.500	0.000	26.000	44.000	23.500	30.500
4HV	25.000	24.000	3.000	2.000	35.000	22.000	16.000	11.000	2.500	2.000	61.500	52.000	19.000	13.000
5HV	25.500	28.000	5.000	4.000	21.000	21.000	11.500	7.500	4.000	5.500	64.000	73.000	27.000	22.000
6HV	23.000	21.000	2.500	0.000	16.000	21.000	13.000	11.000	-0.500	1.000	71.000	73.000	12.000	17.000
7HV	21.000	22.500	2.000	5.300	27.000	22.500	13.500	10.500	1.000	1.000	55.000	57.000	23.000	24.000
8HV	15.000	18.000	8.000	11.000	32.000	26.000	9.000	8.500	7.000	5.000	40.000	46.000	19.000	13.500
9HV	24.000	21.500	3.500	0.000	16.000	45.000	11.000	14.000	2.000	5.000	79.000	59.000	13.000	19.000
10HV	29.500	23.000	5.000	2.000	35.000	30.000	10.000	11.500	1.000	0.000	52.000	69.000	27.000	16.000
11HV	26.000	19.500	1.000	1.000	27.000	10.500	14.000	12.500	1.000	-1.000	69.000	44.000	18.000	25.000
12HV	23.500	25.000	1.000	3.000	29.000	24.000	13.000	13.000	-1.000	0.000	59.000	61.000	17.000	12.500
13HV	26.000	21.000	2.000	3.000	17.000	21.000	11.000	11.500	-4.000	-4.500	75.000	62.000	23.000	24.000
14HV	27.000	28.000	1.000	1.000	29.000	35.000	11.500	18.000	-5.000	-3.000	57.000	76.000	17.000	9.000
15HV	22.000	27.000	3.000	5.000	37.000	32.500	12.000	10.000	4.000	2.000	53.000	60.000	9.000	9.000
16HV	22.000	22.000	3.000	1.000	15.000	21.000	9.000	9.000	-3.000	-5.000	65.000	72.000	22.500	25.000
17HV	22.500	24.000	5.000	3.000	31.000	17.000	13.000	11.000	8.000	6.000	59.000	68.000	14.000	9.000
18HV	24.000	24.500	2.500	3.000	21.000	22.000	16.500	15.000	2.500	1.500	65.000	59.000	11.500	10.000
19HV	19.500	18.000	1.000	2.500	26.500	22.000	11.000	12.000	2.000	-2.000	63.000	47.500	28.000	23.000
20HV	26.000	24.000	1.000	2.500	28.000	23.000	17.000	12.000	1.500	2.000	58.000	62.500	16.500	24.000
21HV	27.000	31.000	9.000	6.000	25.000	29.000	11.000	11.000	4.000	4.000	47.000	55.500	8.000	11.000
22HV	17.000	17.000	2.000	2.000	25.000	26.500	15.500	12.500	1.000	0.500	68.000	85.000	7.000	7.000
23HV	29.000	29.500	2.000	0.000	17.000	26.000	9.000	12.500	2.000	2.000	72.000	68.000	16.000	8.500

(L): left, (R) right

Hallux Valgus Raw Data (Continued)

ID	AOG (L1)	AOG (R1)	AOG (L2)	AOG (R2)	GENDER	DOB	X-RAY DATE	AGE (yrs)	WEIGHT (kg)	HEIGHT (m)	BMI	INCLUSION	NO. OF FEET
1HV	5.000	15.000	5.000	15.000	F	13/02/1940	5/11/2003	63	55.000	1.440	26.524	L	1
2HV	7.500	2.000	12.000	0.000	F	10/05/1943	25/11/2003	60	58.000	1.493	26.020	L	1
3HV	16.000	11.000	13.000	17.000	M	2/12/1936	27/11/2003	67	92.500	1.690	32.387	L	1
4HV	15.500	13.500	18.000	19.000	F	18/05/1929	27/11/2003	74	57.500	1.615	22.046	B	2
5HV	12.500	12.500	10.000	9.500	F	15/10/1958	27/11/2003	45	56.500	1.666	20.356	B	2
6HV	15.000	8.000	14.000	6.000	F	16/09/1939	24/11/2003	64	55.000	1.640	20.449	R	1
7HV	11.000	10.500	10.000	13.000	F	13/11/1928	24/11/2003	75	60.500	1.525	26.015	B	2
8HV	8.000	12.000	7.000	11.000	F	31/05/1932	28/11/2003	71	60.000	1.595	23.585	B	2
9HV	1.000	8.500	0.500	-1.000	F	30/07/1937	28/11/2003	66	89.000	1.574	35.924	R	1
10HV	15.000	11.500	16.000	11.500	M	13/04/1941	11/12/2003	62	95.000	1.900	26.316	B	2
11HV	16.000	15.000	13.000	14.000	F	27/04/1924	2/12/2003	79	79.000	1.565	32.255	L	1
12HV	8.000	10.000	9.500	11.000	F	1/07/1957	3/12/2003	46	63.500	1.668	22.823	B	2
13HV	5.000	13.000	5.000	13.000	F	11/09/1931	4/12/2003	72	58.000	1.598	22.713	R	1
14HV	0.000	17.000	4.000	14.000	F	3/03/1947	22/12/2003	56	60.000	1.650	22.039	B	2
15HV	6.000	8.000	2.000	11.000	F	5/07/1932	4/12/2003	71	53.500	1.645	19.771	B	2
16HV	9.500	9.500	6.500	2.500	F	1/06/1953	8/12/2003	50	74.500	1.585	29.655	R	1
17HV	10.000	1.000	21.000	2.000	F	5/09/1947	5/12/2003	56	73.000	1.584	29.095	L	1
18HV	5.000	14.000	5.000	19.000	F	1/04/1948	5/12/2003	55	65.500	1.520	28.350	B	2
19HV	11.000	14.000	7.000	18.500	F	29/08/1948	11/12/2003	55	66.500	1.520	28.783	B	2
20HV	19.000	23.500	20.500	17.500	F	14/03/1944	12/01/2004	60	59.500	1.638	22.176	B	2
21HV	13.000	15.000	11.000	17.000	F	21/03/1938	29/12/2003	65	67.500	1.500	30.000	B	2
22HV	5.000	12.000	5.500	13.000	F	9/06/1950	31/12/2003	53	63.500	1.605	24.650	B	2
23HV	7.000	10.000	5.000	12.500	F	1/02/1959	19/01/2004	45	57.000	1.616	21.827	R	1

(L1): first left footprint, (R1): first right footprint; (L2): second left footprint; (R2): second right footprint

Control Raw Data

ID	CIA (L)	CIA (R)	LIMA (L)	LIMA (R)	HAA (L)	HAA (R)	FIMA (L)	FIMA (R)	FMPD (L)	FMPD (R)	LAT SD (L)	LAT SD (R)	RFA (L)	RFA (R)
1C	22.000	22.500	6.000	6.000	9.000	14.000	10.000	9.000	0.500	3.000	71.000	66.000	21.000	12.000
2C	38.500	38.000	2.000	1.000	12.000	13.500	5.000	9.000	6.000	6.000	85.000	79.000	27.500	23.500
3C	25.000	18.000	1.500	6.000	15.000	16.000	10.000	6.000	-2.000	6.000	78.000	90.000	24.000	19.000
4C	22.000	22.500	7.000	6.500	0.000	0.000	0.500	7.000	4.000	5.000	76.000	74.000	14.000	15.000
5C	21.000	19.500	4.000	4.000	9.500	18.000	6.500	10.000	10.000	7.000	70.000	72.000	21.500	22.000
6C	24.000	21.000	2.000	9.000	10.500	11.000	9.500	9.000	0.000	2.500	81.500	75.000	15.000	15.000
7C	30.000	26.500	1.000	2.000	7.000	9.000	10.000	9.000	-1.500	0.000	80.000	89.000	12.000	11.000
8C	23.000	24.000	4.500	2.500	0.000	7.500	10.000	8.000	2.000	-1.000	66.000	80.000	35.000	24.000
9C	19.000	20.000	1.000	0.000	6.000	9.500	7.500	8.500	4.000	2.000	84.000	75.000	21.500	25.000
10C	25.500	28.000	2.000	0.000	17.500	10.000	8.000	7.000	3.000	0.000	81.000	70.000	29.000	35.000
11C	29.000	25.000	2.000	5.000	16.000	14.000	12.000	11.000	-1.500	0.000	72.000	80.000	26.000	25.000
12C	28.000	26.000	2.000	0.000	11.000	14.000	8.500	10.500	-2.500	-2.000	70.000	83.000	10.000	5.500
13C	27.000	28.000	2.000	2.000	12.000	14.000	10.000	12.000	5.000	3.000	86.000	85.000	20.000	10.000
14C	20.000	23.500	2.000	4.000	9.000	10.000	10.000	5.500	2.000	1.000	67.000	70.000	9.000	18.000
15C	31.500	34.000	4.000	4.000	12.000	18.000	8.000	9.000	1.500	0.000	87.000	82.000	16.000	18.000
16C	25.000	26.000	2.000	0.000	4.000	9.500	6.000	8.500	-2.000	-3.000	67.000	79.000	17.000	15.000
17C	28.000	32.000	4.000	9.000	6.000	0.000	8.000	7.000	-0.500	1.000	85.000	90.000	13.000	13.500
18C	15.000	17.000	2.000	3.000	7.500	7.500	13.000	10.500	-3.000	-4.000	76.000	83.000	16.000	19.000
19C	23.000	23.000	4.000	2.000	6.000	4.500	11.000	8.000	-6.500	-5.500	78.500	70.000	22.500	18.000
20C	25.000	21.000	1.500	10.000	13.000	10.000	8.000	5.500	4.000	3.000	68.000	71.000	12.500	6.000

(L): left, (R) right

Control Raw Data (Continued)

ID	AOG (L1)	AOG (R1)	AOG (L2)	AOG (R2)	GENDER	DOB	X-RAY DATE	AGE (yrs)	WEIGHT (kg)	HEIGHT (m)	BMI	INCLUSION	NO. OF FEET
1C	0.000	8.000	0.000	12.000	F	28/10/1939	13/01/2004	65	62.000	1.600	24.219	B	2
2C	14.000	14.000	15.000	15.000	F	3/10/1940	15/01/2004	64	87.000	1.595	34.198	B	2
3C	12.000	5.000	8.000	6.500	F	1/09/1935	15/01/2004	69	89.000	1.572	36.015	B	2
4C	13.000	17.000	14.500	13.000	M	5/04/1925	14/01/2004	79	74.000	1.684	26.094	B	2
5C	13.000	6.000	12.000	10.000	M	25/03/1940	11/02/2004	64	83.500	1.698	28.961	B	2
6C	18.000	13.500	16.000	13.500	F	25/06/1937	15/01/2004	67	67.500	1.595	26.533	B	2
7C	8.000	9.000	10.000	10.000	M	15/04/1976	21/02/2004	28	70.500	1.752	22.968	B	2
8C	11.000	17.000	10.500	17.000	F	5/04/1953	28/01/2004	51	80.000	1.535	33.953	B	2
9C	3.000	8.500	5.000	4.000	F	28/10/1934	30/01/2004	70	59.500	1.640	22.122	B	2
10C	11.000	18.000	13.000	18.000	F	27/05/1929	5/02/2004	75	81.000	1.535	34.377	B	2
11C	5.000	8.000	6.000	5.000	F	9/08/1965	28/01/2004	39	71.500	1.605	27.756	B	2
12C	15.000	13.000	13.500	10.000	M	14/07/1941	20/02/2004	63	84.500	1.775	26.820	B	2
13C	5.000	11.000	17.000	13.000	F	28/05/1950	11/02/2004	54	71.500	1.490	32.206	B	2
14C	5.000	10.000	2.000	9.000	F	9/10/1955	9/02/2004	49	73.000	1.740	24.112	B	2
15C	9.000	12.000	12.500	7.000	F	17/09/1922	5/02/2004	82	64.000	1.590	25.315	B	2
16C	7.000	22.000	12.000	21.000	M	18/02/1973	18/02/2004	31	77.000	1.816	23.349	B	2
17C	2.000	4.000	9.500	6.500	M	2/06/1950	26/02/2004	54	77.000	1.752	25.085	B	2
18C	0.000	7.000	0.000	7.500	F	8/09/1936	18/02/2004	68	87.500	1.648	32.218	B	2
19C	6.000	7.000	8.000	6.000	M	4/12/1971	4/03/2004	33	90.500	1.752	29.484	B	2
20C	10.000	0.000	9.000	0.000	M	23/11/1934	11/03/2004	70	92.000	1.812	28.020	B	2

(L1): first left footprint, (R1): first right footprint; (L2): second left footprint; (R2): second right footprint

Appendix 9

Pearson's Product Moment Correlations for Hallux Valgus Group

	CIA	LIMA	HAA	FIMA	FMPD	LAT SD	RFA	AOG
CIA	1.000							
LIMA	-0.96	1.000						
HAA	0.075	-0.063	1.000					
FIMA	0.165	-0.492	0.264	1.000				
FMPD	-0.006	0.500	0.199	-0.185	1.000			
LAT SD	0.117	-0.565	-0.042	0.414	-0.366	1.000		
RFA	-0.163	-0.014	-0.200	-0.414	-0.137	-0.209	1.000	
AOG	0.028	0.115	-0.195	0.045	-0.047	-0.195	0.195	1.000

Pearson's Product Moment Correlations for Control Group

	CIA	LIMA	HAA	FIMA	FMPD	LAT SD	RFA	AOG
CIA	1.000							
LIMA	-0.192	1.000						
HAA	0.191	-0.243	1.000					
FIMA	-0.076	-0.329	0.330	1.000				
FMPD	0.047	0.257	0.192	-0.386	1.000			
LAT SD	0.316	-0.039	0.124	0.046	0.010	1.000		
RFA	0.091	-0.216	0.065	0.034	0.102	-0.101	1.000	
AOG	0.384	-0.292	0.038	-0.235	0.106	0.054	0.162	1.000